WORLD CLIMATE RESEARCH PROGRAMME

WORLD OCEAN CIRCULATION EXPERIMENT

CLIMATE VARIABILITY AND PREDICTABILITY

WOCE/CLIVAR REPRESENTATIVENESS AND VARIABILITY WORKSHOP

Fukuoka, Japan
17-20 October, 2000

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WOCE/CLIVAR Representativeness and Variability Workshop

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The Venue

The workshop took place for 4 days (17-20 October 2000) at the hotel Takakura in the city of Fukuoka, Kyushu, Japan.

Introduction

The World Ocean Circulation Experiment (WOCE) was a large, international program which was formulated with two overarching goals (WCRP-11, 1988):

(1) To develop models useful for predicting climate change and collect data necessary to test them, and
(2) To determine the representativeness of the specific WOCE data sets for the long-term behavior of the ocean and to find methods for determining long-term changes in ocean circulation.

As field programs and data analysis developed during WOCE, various workshops have been held to facilitate international collaboration towards the WOCE goals. Most of these have been regional in nature [Pacific, South Atlantic, Southern Ocean, Indian Ocean, and North Atlantic]. This workshop differs that it

(a) Focused mainly on WOCE goal 2, and
(b) Was global in nature.

The various WOCE data sets are quite different in character. This can be seen by comparing two of the data sets: one-time hydrography and satellite altimetry. The one-time WOCE Hydrographic Programme (WHP) sought to broadly sample all of the major ocean basins (outside of the arctic) with high quality hydrographic and tracer data. For some ocean basins like the Indian Ocean, this occurred over a relatively short period, of order one year. For other ocean basins like the Pacific Ocean, the time period spanned a decade, since some key sections (for example, sections at 24° and 47° N in the Pacific) were not repeated in WOCE but relied on data collected in 1980's. The collection of data in the WHP will define a benchmark for the state of the ocean during WOCE. However, here is one important issue; how typical may this benchmark be, compared to the historical data? And to what degree are the WHP data "synoptic"? Or put another way, to what extent did the ocean substantially change DURING the WOCE sampling? These questions illustrate the issue of representativeness, one important aspect of WOCE goal 2. The altimeter data span a period from 1992 to the present, contain no record gaps, re-sample the ocean every 10 days (for TOPEX/POSEIDON), and cover most of the world ocean except the arctic and the far Southern Ocean. They can not be directly compared with historical data since no comparable data set exists (although there were previous short time series in GEOSAT, for example). Thus the altimeter can better address one issue about representativeness (synopticity), than the other (comparison to historical record). Yet how do we combine these two very different data sets as well as others?

Development of new ocean models has progressed during the WOCE experiment and we are now on the verge of combining data and models together in order to obtain the best dynamical method of integrating all of the diverse WOCE data sets. Here arise two other issues about representativeness; how consistent are the various WOCE data sets with one another and how well can models (that assimilate or not) "represent" the data? Model/data comparisons cannot ignore that, for the most part, the ocean is forced by the atmosphere, and that atmospheric/oceanic fluxes are neither steady nor particularly well "measured". Therefore one can not escape from the fact that the state of the atmosphere and its variability in WOCE are potentially as important as the state of the ocean.

Another aspect of WOCE goal 2 is to develop understanding of variability so that better climate models and observations can be combined in the future. This is squarely in the domain of the Climate Variability and Predictability Study (CLIVAR), which seeks to understand interannual, decadal and longer periods of climate variability. Scientific hypotheses continue to develop about the different roles of the atmosphere and ocean in climate variability. These will guide what process experiments will be needed and what sustained measurement systems of the future will look like. As far as the ocean is concerned, our understanding of the variability as measured in WOCE and its potential sources is critical for progress in defining both CLIVAR and the Global Ocean Observing System (GOOS) envisioned to provide sustained observations of the ocean in the decades ahead.

Thus we see the need to use WOCE to look backward and forward in time, and have configured this workshop with some specific goals, which are as follows:

- To review information gained on seasonal to interannual variability during WOCE,
- To assess information gained on decadal variability from comparison of WOCE and pre-WOCE data,
- To estimate the impact of this variability on the representativeness of the WOCE (particularly WHP) data sets and derived quantities (e.g. heat and freshwater fluxes),
- To review the ability of models to represent seasonal and longer-term ocean variability and the variation in water mass properties, volumes and formation rates,
- To identify, and take steps to initiate, data analysis and modeling research needed to better assess the representativeness of WOCE data sets and derived quantities,
- To identify the principal mechanisms (e.g. local or remote air-sea exchange, advection, propagation, coupled air-sea processes) behind the oceanic signals of climate variability as measured in WOCE, and
- To make recommendations based on the workshop conclusions for the design of future research (CLIVAR) and operational (GOOS) observing systems.

The organizers of this workshop note that variability was one central characteristics of the Japanese observational programme and one of its main scientific foci in WOCE. They also note that none of the previous workshops was held in Asia. Thus, another purpose of the workshop was to create a forum in Japan which might entrain new people and ideas into the discussion of the themes of the workshop. We are pleased that this workshop was hosted in Fukuoka, Japan, and wish to thank the Local Organising

Committee, chaired by Shiro Imawaki, for the excellent logistical support and facilities in Fukuoka. In total, there were 65 posters presented and a total number of registered attendees of 81 (for the full list see appendix 3).

The Workshop consisted of plenary sessions with one or two keynote talks presented in each to stimulate thinking along the lines of each session. See the Agenda, appendix 1. After the talks, all of the posters in a given session were briefly introduced and the workshop then shifted to the poster session room. Because of the more than adequate space, it was possible for all posters from all sessions to be up and in place for the entire workshop. Abstracts of all presentations are found in appendix 2. Various special focus topics were suggested by the Science Organising Committee and Workshop Attendees and these evolved into six special sessions: three each on the penultimate and final days of the Workshop. The final plenary session was a summary of all of the various formal and informal sessions, with a discussion of the major results presented and issues discussed. Below, a brief summary is presented for each of the Sessions and Focus Discussions by their respective chairs.

General Scientific Sessions

1) Global views of WOCE Variability: data and models (chair Bill Large)

The principal speakers in this session Sergey Gulev (air sea fluxes) and Dudley Chelton (satellite altimetry). As advertised, the Session did present a global perspective of the following: surface fluxes, satellite observations, ocean observations, ocean models, coupled models and ocean state estimation. There was a clear demonstration that in integrating the surface heat fluxes from VOS measurements to give implied northward heat transports, the uncertainties grow far too much for the calculation to be of much use. However, over much of the North Atlantic for example, the uncertainties (eg. sampling) are not too large for the implied divergence of the ocean heat transport to be useful in constraining direct estimates from ocean sections. The converse is also true.

Combining satellite scatterometer winds with microwave SSTs revealed regions of enhanced wind stress and curl associated with oceanic fronts, with implications for frontal dynamics and biological production in such regions. The NSCAT and QuikSCAT data have allowed quantitative assessment of the accuracy of the wind field analyses produced by the ECMWF and NCEP operational weather forecast models. The results show a significant improvement in ECMWF between the October 1996-June 97 period of the NSCAT data record and the August 1999-present period of the QuikSCAT data record. The most significant improvement has been in the tropics, but the accuracy of the operational analyses of 10-m winds has also improved significantly at middle and high latitudes. It should be noted, however, that the spatial resolution of the operational analyses are still limited to scales longer than approximately 500-700 km. As a consequence, ECMWF and NCEP considerably underestimate the intensities of the derivative wind fields (divergence and curl).

The results shown in the Session display variability almost everywhere and in nearly every quantity observed during WOCE. In particular, the 8-year TOPEX data record has detected energetic variability on time scales from monthly to interannual and space scales from 100 km to global. On seasonal, interannual and even decadal time scales the variability matches that observed in the atmosphere. Of particular importance here are the repeat XBT lines. Ocean models, both hindcasts and coupled to an atmosphere, are being used to extend this ocean variability in time and space, and to investigate mechanisms for its generation and propagation.

2) Principal Mechanisms for Variability (chair D. Webb)

The principal speakers in this session were Jim Hurrell and Kimio Hanawa. Hurrell spoke about the state of the atmosphere during WOCE. It is expected that much of the oceanic variability is forced by the atmosphere. In both the Southern Ocean as well as the North Pacific and Atlantic, there was a low anomaly of atmospheric pressure over high latidudes driving higher than average westerly winds over the subpolar and northern subtropical oceanic gyres. In the N. Pacific, this is reflected in a low North Pacific Index (NPI). Hanawa presented evidence that fluctuations in the NPI and the Kuroshio properties were 90º out of phase and suggested that this was indirect evidence of a coupled oceanic/atmospheric process involving the two phenomena. In the N. Atlantic, this low pressure over Iceland is associated with a high pressure in the subtropics resulting in a high anomaly in North Atlantic Oscillation (NAO) Index. Bill Dewar's poster examined an analytic/QG model of a coupled interaction at mid-latitudes of this process and again suggested that this may be part of a coupled mode between the atmosphere and the ocean. This issue was re-visited in the focus group discussion later (see below).

Other topics in this session were

- the effects of oceanic shear on the propagation of oceanic variability (Killworth)
- the importance of Ekman pumping on rapid barotropic variability (Webb)
- the role of Kelvin and Rossby waves in connecting Pacific and Indian Ocean variability in the Indonesian Passages (Yang)
- the use of WOCE hydrography in the study of the changes in the thrmohaline flows in the Atlantic to the NAO (Dobroliubov)
- the importance in eddy fluxes in affecting the structure of the meridional overturning circulation in the tropics (Danabasoglu).

3) Model/data comparisons: where are we? (chair P-Y Le Traon)

The session had one invited presentation (D. Stammer) and eight posters. In his invited presentation, D. Stammer presented results on model and data comparison at high frequencies and at the mesoscale. He showed that models have now significantly improved and can be used to help the data interpretation. He then focused his presentation on the data assimilation and efforts underway to derive a consistent, global 4D description of the ocean state. First assimilation results at low resolution are encouraging. The optimization is working and, in particular, heat flux errors appear to be corrected in the right way to reduce the misfit between data and models. The current work deals with the comparison of the outputs of the assimilation system with WOCE data. Future (GODAE) plans are to improve the model resolution and physics.

One of the main lessons from this session (and from posters in other sessions) is that unconstrained models do show skills in reproducing some variability signals. They can thus be used to better explore these variability signals. Many illustrations of this joint use of data and models have been presented in the workshop. The next and complementary step will be to merge the data and model through data assimilation.

4) Pacific/Indian Variability (chair S. Imawaki)

There was one oral presentation and 20 posters. Many topics were discussed and the oral presentation by Dean Roemmich showed:

- Upper ocean, basin-wide meridional transport adjusts relatively quickly to wind stress changes.
- The amplitude of interannual variability of net meridional heat transport. The mean value at mid-latitude of North Pacific is 0.8 PW, which is close to the estimate from surface heat flux derived from ECMWF fields.

The poster presentations are summarized as follows:

Pacific Ocean

- The Oyashio, the western boundary current of the North Pacific subarctic gyre, was studied; flow field and transport were estimated from the combination of in situ observation and altimetry data, and its intrusion to the south was described.
- The Kuroshio, the western boundary current of the North Pacific subtropical gyre, was studied; transport south of Japan shows small seasonal signal, which fact is explained by the presence of the Izu-Ogasawara Ridge preventing the signal from the interior region to penetrate into the Philippine Basin. Also shown was that the observed decadal variability of the transport compares well with the Sverdrup transport with some delay.
- Climatological mean temperature sections of upper ocean have been obtained from VOS high-density XBT network for the North and South Pacific. Upper ocean velocity sections are also being obtained by VOS ADCP program.
- Subsurface subtropical fronts were studied from water property distributions. Also, interannual variability of the salinity minimum of the North Pacific Intermediate Water was studied.

- Bottom water property in the North Pacific was studied from repeat of one-time hydrography; the water has warmed from 1985 to 1999.
- Interannual variability of surface current in the tropical Pacific was studied by using drifter data; conditions during El Nino are compared with those during La Nina.
- Decadal variability of Ekman pumping velocity was derived from sea-level pressure field for 100 years, and climatic regime shifts in 1940's and 1970's are shown.
- Method of estimating heat budget of the mixed layer was studied and applied to the North Pacific.

Marginal seas of the Pacific Ocean

- Response of the South China Sea to the monsoon was studied.
- The Kuroshio path variation in the East China Sea and Tokara Strait was studied.

Indian Ocean

- Mass and heat transports across the equator due to the seasonal and intraseasonal variation of wind stress were discussed.
- Seasonal signal is found to penetrate down to the 3,000 m depth in the flow field.
- Decadal change of deep water masses were studied; temperature and salinity in the main thermocline (on neutral density surface) at 20°S decreased from 1960's to 1980's.
- Meridional net heat transports at 32°S were compared 1936, 1965 and 1987.

5) Southern Ocean and Arctic Variability (chair N. Bindoff)

This session had two invited talks and 11 posters. The main focus areas for this session were transport variations of the Antarctic Circumpolar Current, the Antarctic Circumpolar Wave, short term changes and decadal changes in water masses of Southern Ocean Origin and in the Arctic Region.

The key results from the posters and invited talks are summarised below. A new method for estimating the transport anomalies on WOCE SR3 section between Tasmania and Antarctica was presented in the talk by Bindoff. This method, based on the correlation obtained from CTD data between steric sea-level height and depth integrated steric anomaly, was used to show the rapidly changing transport variation that were observed south of Australia. The rapidity of the transport variations (weeks time scales) showed how important it is to monitor transport variations time scales. Striking water mass changes in bottom waters on both short time scales, and longer time scales in Drake passage were also shown. Drake Passage AABW and Scotia Sea AABW show considerable changes in position between repeated hydrographic sections, only a few years apart. The changes in the Scotia Sea are thought to be related to changes in the path of AABW from the Weddell Sea through the Scotia Island chain. On longer time scales comparison of hydrographic data in the Indian, Pacific and Atlantic Ocean have all shown that SAMW and AAIW have changed. A coherent pattern of freshening of AAIW (suggesting a freshening of surface waters) and a cooling and freshening of density surfaces of SAMW consistent with a warming of this water mass were observed. South of the SAF only the near surfaces waters (below the T min layer) and above the salinity maximum show significant difference in water mass characteristics. The exact reason for this is not clear but could be an increased transport of UCDW across the ACC. In the Arctic Region quite distinct changes have been observed in the ocean circulation, sea-level pressure (the Arctic trough is now deeper), precipitation (has increased) and temperature (now warmer) over the last 100 years according to the oral presentation by Andrey Proshutinsky. The changes in the Arctic region seem to parallel the changes in the Southern Ocean over the last 30 years (Circumpolar trough is now deeper, suggesting stronger westerlies and from reanalysis runs by NCEP increased rainfall).

6) Atlantic Variability (chair P. Koltermann)

The lead speaker in this session was John Gould, who spoke about Oceanic variability in the mid to high latitude N. Atlantic Ocean. The overview, with material provided by Bob Dickson, high-lighted the extremely variable character of the Atlantic on all time-scales and the nature of this variability. He also summarised the findings of last years North Atlantic Workshop in Kiel. As the main conduit between both poles the Atlantic shows strong and rapid changes induced via the intermediate and deep waters of high latitudes. During WOCE the role of several elements of this adjustment process have become clear: the role of deep convection in the formation of intermediate water masses, the rapid delivery of newly formed intermediate waters from high latitudes by boundary currents to moderate latitudes, and how the full-depth circulation of the North Atlantic, and associated meridional heat transports, are closely linked to large-scale changes in atmospheric forcing (i.e. the North Atlantic Oscillation). The coupled ocean-atmosphere system of the Atlantic Ocean has marked and obvious effects on its bordering continents, and also ties into the global variability pattern, as shown for the most recent ENSO event.

A prominent feature of its variability was the reaction of the North Atlantic circulation to the dramatic drop in the NAO index from its all-time high in the winter of 1995/6 and the as dramatic recovery. Although definitely not adequate for a coverage of decadal changes, the WOCE data set captured a prominent and so far unreported large-scale event in both atmosphere and ocean.

In all, eight posters covered various aspects of the Atlantic Ocean variability, from changes in the deep hydrographic constituents and water masses, in boundary current transports and ocean-wide transports of heat and fresh-water. Exchanges processes with the Arctic Ocean and the European North Polar Mediterranean Seas have also been described. Several modelling experiments shown promising insights into the physics underlying these changes, and indicate that modellers and observationalists finally may start talking the same language.

Focus Group Discussions

1) Representativeness: Seasonal/Interannual Variability (chair D. Roemmich)

Relevant datasets:

Satellite: TOPEX/POSEIDON, SST

In situ:
Broad-scale XBT (mostly north of 30^{o}S)
High resolution XBT (limited to N. Atlantic and Pacific – including SO and IO chokepoints)
Repeat hydrography (few in number)
Repeat ADCP lines (few in number)
Time-series stations (Bermuda, Hawaii, Canary Is)
Neutrally buoyant floats (single level velocity, 1000m or other depth)
N. Atlantic PALACE array, including profile information
Air-sea fluxes
Moored arrays
Sea level stations
SSS measurements, especially in western tropical Pacific

Missing:

Mid-depth and deep ocean variability on basin to global scales
Salinity and velocity variability on basin-to-global scales
Knowledge of the scales of variability of salinity and velocity

a) What was learned about seasonal-to-interannual (SI) variability of the oceans during WOCE?

In the upper kilometer, TOPEX/Poseidon altimetry (with its high correlation to thermocline variability) plus the relatively high density of *in situ* measurements collected during the WOCE era make it feasible to reproduce and track the variability of the upper ocean density field over much of the globe. There are important limitations on resolution and in areas that are less well-sampled with *in situ* data. Data assimilation models will provide the best interpretation of the combined data sets - satellite, *in situ,* and atmospheric forcing.

Examples of important WOCE findings relevant to upper ocean variability are given in the following. The list is not complete because not all of our community is present here, but it is illustrative:

- Hemispheric asymmetry in seasonal cycle (T/P)
- Rossby waves have been observed in satellite SSH, SST and other fields, but propagate 1.5 – 2 times as fast as linear theory. This is well explained by the background potential vorticity of the mean flow.
- Description and modeling of Antarctic Circumpolar Wave

- Interannual variability in upper ocean mass transport and heat transport in the tropical and subtropical Pacific is about 30% of the mean (High Resolution XBT/XCTD). Present limiting factors are depth of measurements, number of realizations and accuracy of the wind field. A tendency is seen for upper ocean geostrophic transport on basin scales to balance Ekman on sub-annual periods.
- Seasonal, monsoonal and interannual variability in the Indonesian throughflow. The variability is the same order as the mean. This is one of the reasons that single measurements of the throughflow have produced disparate results. Intra-annual variability is dominant in the eastern part of Indonesia, compared to the dominance of seasonal and higher frequency variability in the exit passages of the Indian Ocean.
- Interannual variability in the tropical Indian Ocean is of the same order as in the Pacific (T/P).
- Detection of SI variability in EKE in some regions (e.g. N. Pacific subtropical countercurrent, Kuroshio Extension)
- Small amplitude of seasonality in the Kuroshio transport south of Japan. Rather, variability of Kuroshio transport is caused by propagation of mesoscale eddies into the current (T/P, repeat ADCP). The Agulhas is also found to have low seasonality.
- Interannual variability in the position of the subarctic front in the North Atlantic, driven by changes in the windstress field, affecting the salinity field.
- Interannual variability in water mass volumes and characteristics in STMW and Tropical Water (Subtropical Underwater).

Below 1 km depth, the repeating measurements of the WOCE era are regional in nature (rather than basin-to-global). There are valuable results for specific regions but few that can be generalized to the large scale. Some of these specific results have importance for model comparisons. As above, the following list is not complete, but illustrative of findings.

- Existence of deep seasonal cycle in velocity at some tropical locations
- Lack of seasonal variability in Denmark Strait overflow
- Interannual variability in the depth and characteristics of the winter mixed layer in the Labrador Sea.
- Variability in the characteristics of the LSW can be traced downstream and used to estimate spreading rates in the eastern margin of the subpolar gyre. It is becoming apparent that the spreading rates may also change on interannual timescales.

b) *What are the implications for the interpretation of limited duration WOCE datasets (e.g. WHP 1-time, current meter arrays, floats,)?*

Because of the limited observations of deep variability during WOCE, a rigorous answer to this question is not possible. By sampling the World Ocean within a period of 7 years, WOCE limited the internal variability in its data set to shorter time scales (i.e. decadal change is not present in WOCE). However, since the spectrum of variability on sub-decadal periods is not known in the deep sea, the representativeness issue is still undetermined. Existing repeat data show that the spectrum of variability includes significant energy at seasonal to interannual periods. Successful quantitative interpretation of WOCE deep-ocean data sets poses a challenge, requiring more sophisticated approaches such as time-dependent inverses and data assimilation modeling.

2) Representativeness: Decadal Variability in WOCE (chairs P Koltermann & N. Bindoff)

There was a wide ranging discussion about the WOCE period in terms of its representativeness in data, models and phenomena and to earlier time prior to WOCE.

The value of WOCE experiment for Decadal Time scales

The focus group thought that it was important to recognise the value of the WOCE experiment for starting new work focussing on long term changes. Formally WOCE was not attempting to address these long term changes but rather the new results and outcomes that have been achieved as a result of the observations. The WOCE period has resulted in the most complete in data coverage and quality. In parallel there has been significant model development which among the observational community are gaining recognition as a tool with skill for making predictions and for determining the underlying mechanisms that are operating. There was discussion about whether we would do WOCE the same way again. The view was that the WOCE experiment was a success because it encompassed the full water column and was global in scale. It has lead to the development new improved models, data to test these models and most importantly the recognition that oceans are changing, complex and interact with the atmosphere in a coupled system. The data obtained from the WOCE experiment are an essential legacy for future observing systems and programs such as CLIVAR. There is a recognised need for further climate model development suitable for the study of long time scales, e.g. in parameterisation of internal ocean mixing and surface fluxes.

Decadal differences are pervasive

There were discussions about the observed changes within the deep water column, and at shallower depths. There was discussion about the role of the atmosphere on driving the observed temporal and spatial variations on all time scales. The variability of the ocean is being seen on ocean basin scales, and on global scales. The differences or variations are pervasive throughout the entire ocean basins and can not be easily resolved from the relatively incomplete and short time scale of the WOCE experiment.

Decadal differences observed during the WOCE period need to be monitored

There was recognition that the WOCE period was different from earlier periods and likely to differ from the future. This fact highlighted the need for sustained observations over the global oceans that can be used to monitor the evolution of the oceans. In addition it was appreciated that no observing systems would be fully complete to capture all time and space scales (including depth). This fact means that the community must continue to develop modeling and synthesis activities to allow the interpretation of the new data and to reduce the effects of aliasing which can be serious in incomplete data.

Need to focus on mechanisms of decadal changes

The focus group recognised that the ocean circulation and ocean change on decadal time scales is a coupled system, driven by atmosphere on the one hand, and yet feeding back heat and thus providing forcing to the atmosphere. It was also recognised that the exact role of the ocean in the propagation and energy partitioning in the coupled ocean-atmosphere system and within each of the elements of the coupled system was not clear. This was an important issue in understanding the climate system, and central in our capacity in predicting the future climate.

What should future programs include that are not currently in WOCE?

The focus group recognised that the WOCE program had missed important aspects of the Climate System. Future programs should include the Arctic Ocean. Sea ice must be included because of its role on feedback in the atmosphere and on the ocean through limiting the exchange of heat and dissolved gases. Sea-ice is predicted to be much reduced in extent under climate change, and this will impact greatly on climate and has direct implications for the production of bottom water and hence on the meridional overturning circulation.

Resolution of seasonal cycle

Many processes depend strongly on the seasonal cycle, such as the seasonal heat transport in the Ekman Layer driven by seasonal winds. The seasonal cycle needs to be well resolved to estimate the mean transports of heat and freshwater by the near surface layers in the coupled system. The global oceans present special problems for the measurement of precipitation. It is important to know how precipitation varies on decadal time scales and to some extent such changes can be monitored through the measurements of sea-surface salinity.

3) Towards better surface flux estimates (chair W. Large)

Session 1 and others spawned discussion on the air-sea fluxes. Two specific questions were addressed. First, what are the best surface fluxes produced for WOCE? For each flux type the group considered what was available globally throughout the 7 years of WOCE, what is available only over certain regions, or only part of the WOCE period, and what are the known caveats with using these products.

It was noted that the issue of reliability of surface flux fields has been extensively addressed by the WCRP/ SCOR Working Group on Air-Sea Fluxes which has recently produced a comprehensive report on this issue. We recommend that the WOCE community utilise this report (available from http://www.soc.soton.ac.uk/JRD/MET/WGASF/index.html)as a primary source of information regarding surface fluxes. We also draw attention to, and invite participation in the follow up to this report; WCRP/SCOR Workshop, “Intercomparison and Validation of Ocean-Atmosphere Flux Fields”, Washington, DC, 21-25 May, 2001 (http://www.soc.soton.ac.uk/JRD/MET/WGASF or http://www.sail.msk.ru)

Wind velocity/stress : At present the NCEP reanalysis winds are the only consistent global product available throughout WOCE, and hence the best. However, there are discontinuities corresponding to changes in the observing system. So, in terms of trends, the reanalysis are not reliable. Indeed, the WCRP has identified this as a key challenge for the next reanalysis program. There are plans for a reanalysis at ECMWF, but not in the US.

Satellite scatterometer winds have been produced over part of the WOCE period, but be aware of possible aliasing problems in wind fields constructed solely from the single narrow-swath ERS scatterometer data. There are very useful winds over the equatorial Pacific from the TAO moorings and over the Northern midlatitude oceans from Voluntary Observing Ships (VOS), including the operational buoy network. All these product have been cross-compared and evaluated, and scatterometer wind stress could be more accurate than the ground truth. Operational analyses at numerical weather prediction centers frequently change procedures that are reflected in their surface fields, such as the wind, which therefore, should be used with caution. For example, recall the recent improvement in the quality of the ECMWF analyses, which is likely due to the assimilation of ERS scatterometer data. Despite the sparse sampling, these data help constrain the operational analyses in a way that greatly improves the accuracy, especially in the tropics which remains the region of lowest accuracy, but also at middle and high latitudes. Such assimilation is likely to continue to benefit operational analysis and reanalysis during scatterometer missions, so such efforts should be encouraged by future programs such as CLIVAR.

Precipitation : The “best” product would seem to be the CMAP blend of station data, MSU satellite precipitation, and model results. It is a monthly, or bi-weekly, global product, beginning in 1979. Beware of atmospheric models that develop an erroneous ITCZ in the South Pacific, because of the excess precipitation this produces. Also problematic would be if high local rainfall over island or coastal stations were projected too far into the open ocean. It is unclear if these problems contribute to the much greater CMAP precipitation in the tropics compared to the MSU alone. Recently the TRMM satellite mission has started providing precipitation within about 38 degrees of the equator. All of the above suffer from the lack of “ground truth”, which is exacerbated by the difficulty in making representative precipitation measurements at the surface.

Radiation : An important consideration here is that both long-wave and short-wave components should be derived from the same source so that errors in cloud amount tend to cancel. The best radiation fluxes should come from the ISCCP. Although the satellite data to do so have been collected the radiative fluxes have not been produced over the full WOCE period. Since it is difficult to obtain global surface truth, some biases may be present. There are direct radiation measurements over the TAO array. Ship based estimates of the radiative fluxes, obtained from meteorological reports using empirical formulae, are also available for the WOCE period in the SOC data set. Limited comparisons with research buoy measurements suggest that such estimates are in some cases more accurate than those obtained from the reanalysis.

Turbulent fluxes (latent, sensible and evaporation) : There is no acceptable product for these quantities. The VOS and TAO provide the flux parameters over limited regions and it would seem best to correct the NCEP parameters to match. The NCEP relative humidities are always greater than 80%, and need to be reduced, though the transfer coefficient may be providing a correction here. Since whatever correction used are very subjective and universal corrections are unlikely to be appropriate, there is no reliable estimation of these fluxes, globally over the WOCE period. This state of affairs is a shortcoming of WOCE, and should not be allowed to continue through the next decade.

The second question addressed was; how do the dominant patterns of atmospheric variability project on the surface fluxes? The atmospheric circulation during the WOCE period of the 1990s was anomalous in several respects, though more similar to the 1980s than to previous decades. These conditions mean that the ocean surface fluxes during WOCE were not typical, but analysis of long records suggests that this is usual; no short period (5-7 years) is similar to any other such period.

In the Southern Hemisphere the sea level pressure (SLP) was anomalously low over the high latitudes and high over the subtropics. The associated atmospheric circulation led to stronger eastward and southward stress (stronger westerlies) over the middle latitudes. There is some indication of more cooling and less (P-E) over the Southern Ocean, but analysis of changes in Sub-Antarctic Mode Water properties and coupled climate models suggest the opposite. Compared to the 1970s, there was a pronounced weakening of the semi-annual harmonic in zonal wind stress over the ACC, especially in the Pacific sector.

A clear regime shift is seen in the intensity of the Aleutian low pressure center. After about 1976, The North Pacific was dominated by lower than average pressure; negative North Pacific index throughout the WOCE years, except for winter 1993/94. This atmospheric signal most clearly projects onto more ocean cooling and net freshwater flux. Another consequence is stronger mid-latitude westerlies during winter, but there is little signal in the zonally averaged annual mean stress components.

Lower than average pressure in the 1990s was also the case in the mid-latitude North Atlantic, which when combined with higher than normal pressure in the subtropics resulted in the NAO being generally in a positive phase throughout WOCE. This situation strongly affected the Atlantic fluxes poleward of about 40N. In the annual mean the westerlies were very strong in some years and with more interannual variablity than during previous decades. The zonally averaged annual mean heat flux, however, remained near average and less variable. Farther south, the tropical trades were also stronger in the northern Hemisphere, but there is little signal in the mean wind stress components.

The atmospheric phenomenon tied to El Nino is termed the Southern Oscillation (SO), which involves exchanges of air between the eastern and western hemispheres centered in tropical and subtropical latitudes. Thus, it is characterized by the difference in normalized SLP anomalies, Tahiti minus Darwin; the SO index (SOI). A pronounced change toward more negative values is evident since the mid 1970s, including prolonged warm ENSO conditions from 1990-1995, the beginning of the WOCE period. This projects onto somewhat weaker westward wind stress and a small increase in surface cooling, implying that unusual ocean circulation supplied the necessary heat over these years. The lack of interannual and longer period variability in the SOI, is reflected in the fluxes too.

4) Variability Hypotheses (chair D. Webb)

Progress on understanding oceanic variability during WOCE was divided into several themes.

a) Internal Oceanic Variability

Mixing in the ocean has been studied with tracer releases and direct turbulence measurements. The results indicate that vertical diffusivities of 0.1 (cm^2/s) are found in the subtropical gyre (of the N. Atlantic) with locally larger values by an order of magnitude in the deep water near rough bathymetry (in the Brazil Basin). The role of tidal mixing over rough topography must be considered in enhancing the mixing near the ocean bottom.

Planetery Waves can be modified by existing mean oceanic shear. Results suggest that this can affect first order quantities such as the phase speed of internal planetary waves.

Other process of importance were the

- Flux of water into the Arctic
- Sub-mesoscale vortices in the S. Atlantic
- Fast, deep flows in deep western boundary curents
- The role of topography in the deep ocean at high latitudes

b) Variability driven by the Atmosphere

- The NAO was ‘re-discovered’ during WOCE in its importance for organising N. Atlantic Variability
- ENSO was well observed by TOGA and the establishment of the TOGA/TAO array enabled detailed examination of subsequent interannual variability in the tropical Pacific.
- Southern hemisphere modes and the North Pacific Variability were not so well observed in WOCE, the former because of difficulty in sampling and the latter because of the long time scale associated with this variability

c) Coupled Variability

The tropics, especially the Pacific Warm Pool, appear to have the most important role in coupled variability. This results from the large changes in evaporation with elevated oceanic temperatures. The oceanic feedback most probably involves Kelvin and Rossby waves, but this may be affected by mode and intermediate water masses on decadal time scales.

In the subtropics, the effects are less important but may affect the decadal (but not interdecadal) variability. There is some support for this emerging from atmospheric models run with prescribed SST.

d) Other interactions

Other indications of oceanic feedback on smaller scales include the intensification of hurricanes over warm core rings and the tracking of extra-tropical cyclones over the sea ice edge.

5) Model/data Comparisons and Assimilation (chair P-Y le Traon)

The focus group meeting included a review of model/data comparisons (as a follow up of session 3) and a discussion on the perspectives given by data assimilation. More specifically, the group was asked to answer/discuss the following questions/subjects :

a) Consistency between data and models for the different variability signals (intraseasonal, seasonal, interannual, decadal) – where are we?

b) What should be done in the future as far as model/data comparisons are concerned ?

c) Data assimilation and WOCE/CLIVAR : what are the needs and how do we assess the value of a data assimilation system ?

The group first discussed the objectives of model/data comparisons. There are two main objectives; the first one is related to model improvements (one of the main objectives of WOCE); the second one is to use the model as a tool for a better interpretation of the different data sets. As was pointed out in session 3, unconstrained models do show skills in reproducing some variability signals. They can thus be used to better explore these (but only these) variability signals. That a model reproduces a variability signal or more exactly the fraction of this signal which is observable from the existing data sets, does not mean, however, that the model is right. More detailed analyses are often required to validate the physics behind the variability mechanism. The group also emphasized the importance of looking at different ocean models to derive a robust characterization of a given variability signal. This is particularly needed when the data sets are too limited to provide an unambiguous view of these variability signals.

A brief review of model/data consistency for the different variability signals was made based on the experience of focus group participants. At intraseasonal scales, recent results show that model can represent in a deterministic way part of the high frequency, large scale barotropic variability observed in altimeter data. Impressive progresses have been made to represent the mesoscale variability thanks, in particular, to an increase (up to 1/10°) of model resolution. The eddy kinetic energy levels in the model and in the data are now in good to very good agreement (energy levels, space and time scales). At seasonal time scales, models provide a consistent and good representation of the wind-driven adiabatic (and linear) variability. They lead ocean observations for certain signals (e.g. DWBC seasonal variations) and can readily be used to guide the interpretation of observations. The thermohaline driven circulation is not as well represented and models do not provide a consistent view of it. Non-linearities play an important role and model results are sensitive to many parameters (e.g. outflows, bottom topography, mixing). For these signals, model/data comparisons should aim first at validating ocean models (before ultimately using models to better interpret the observed variability). At longer time scales (interannual and decadal), thermohaline (buoyancy forcing) becomes more and more important and models are thus faced with more complex problems. This is mainly true at mid and high latitudes. In the low latitudes and in the tropics, the system remains more linear longer and models continue to show good skills in representing the observed variability.

The existing data sets for validating the variability signals observed in ocean models were clearly felt insufficient. Only surface data (SST and altimetry – although altimetry represents an integral of the interior density field) and a few repeat XBT lines can be used to validate the variability signals observed in models. The situation will improve with ARGO which should allow, in particular, a global monitoring of the mixed layer depth variations, a parameter critical for validating the variability signals due to buoyancy forcing.

What should be done in the coming years was then discussed. First, more detailed analyses could be carried out involving higher order statistics and more elaborated comparisons (e.g. diagnose advection of heat from the data and the model). The use of repeat XBT data and associated analyses (transport and heat fluxes) should be developed further. The group also felt that a more systematic and coordinated approach for the validation of model outputs should be set up. The objective would we to define a comprehensive list of metrics of signals (here for the variability) a model should be able to reproduce (e.g. characteristics of the seasonal cycle of circulation, heat/mass transport variations of WBC...). The group would like to see that list established mainly by observationalists from what they know is unambiguous in the data analyses. A recommendation would be to form a small working group on these issues with the objective to form and maintain this list.

The group finally started a discussion on data assimilation issues. The value of data assimilation for research (WOCE, CLIVAR) was emphasized. WOCE and CLIVAR do need reanalysis providing consistent 4D ocean state estimation; it was recognized that the best use of the data will be ultimately when they are integrated with model and dynamics through effective data assimilation techniques. Observing System Sensitivity Experiments (OSSEs) to analyze the contribution of existing and future observing systems are also required.

This is a challenging task. Several models and data assimilation systems are planned within GODAE. Depending on their configuration, some models will develop more the model resolution with low cost data assimilation systems (e.g. optimal interpolation) while others will remain on low or medium resolutions with more advanced data assimilation systems. Ultimately, the WOCE need is for dynamically consistent 4D ocean state estimation but intermediate products may prove useful for some applications by providing a 4D description of the ocean state close to the observations. As for model/data comparison, metrics to assess the value of data assimilation systems should be developed. This includes metrics defined for model/data comparison issues but metrics specific to data assimilation will have to be developed (e.g. contribution of data assimilation versus data analysis, forecast skill...). Most of these issues are addressed in the GODAE strategic plan.

The group finally discussed the use of ocean state estimation products as initial conditions for a coupled climate model integration. It was noted that the feasibility of this approach is not yet demonstrated as the state estimation is dynamically consistent (within limits) only with the model used to produce it. If used as initial conditions for a different ocean model, then there may be initial transients including long term drift towards the dynamics of any new model.

6) **Future Observations** (chair D. Roemmich)

Given the background (OceanObs99,) plus the experience of WOCE, what is the present status of planning and what modifications and additional planning are needed for ocean observations in CLIVAR etc?

The following topics were discussed by the group.

- Concern exists regarding continuation of *highest* quality satellite observations beyond 2009. High quality satellite altimetry, scatterometer winds and SST are needed.

- Argo (the global profiling float project) is on target for full deployment of 3000 floats by 2005. Continued strong community support and broad participation is needed for this project.

- Deep hydrography – a reasonable plan exists but is seriously undercommitted in the Pacific, Indian, South Atlantic, Arctic and Southern Oceans.

- Time series stations are of high value – the concept and practical execution need better definition. Is it appropriate for time-series stations and air-sea flux reference stations to coincide?

- Recommendations of Melbourne Upper Ocean Thermal workshop (August, 1999) and Oceanobs99, with regard to maintaining broadscale XBT sampling until Argo is installed, are not being followed. There is concern both because the amount of broad-scale temperature profiling is presently in decline and because the transition of the network to line-based sampling (high resolution and frequently repeating lines) may not be possible if XBT resources decline.

- Western boundary current observations. Efficient technologies need to be investigated (e.g. TOPEX/ Poseidon hydrographic combinations, gliders,) to allow adequate sampling and coverage.

What is needed to move from the planning phase to carrying out the observations? The group's discussion included the following points.

- The necessity of building international consortia (consisting of the organizers of the national programs) was strongly underlined, as the means of finding the resources and synergies necessary for any element of the observing system. Partnerships of science and operational agencies are of increasing importance to bring substantial resources to ocean-scale observations.

- Many CLIVAR-relevant observations will be made, and some of them may not carry a CLIVAR label (for reasons having to do with national funding). The situation for some elements of the observing system, e.g. deep ocean hydrography, may be more positive than seen in present versions of the international CLIVAR plan. The need for U.S. participation in decadal reoccupation of deep ocean hydrographic lines was noted.

- A variety of new technologies (acoustic monitoring, gliders, moored profiling CTDs,) show promise for efficiently addressing sustained observational problems. These must be incorporated into the emerging plans as they mature.

- Data distribution and quality verification require significant resources. This group recognizes that resources must be set aside to ensure that data are received from the providers and distributed to agencies and the research community according to CLIVAR requirements. An essential component of this is both the tracking of the observational activities and the overhead associated with distribution of data to the community.

Workshop Conclusion

Some of the session chairs were more assiduous than others in determining the support among the participants for a dedicated issue in the Journal of Geophysical Research, which would collect a number of contributions on the topic of Representativeness and Variability from the participants of the Workshop. Should such a special issue be required, David Webb has agreed to be the special editor. The Workshop SOC will work with Webb and the WOCE IPO staff in following up on this question in the near future. If we proceed, authors should consider having manuscripts ready for submission, by April of 2001.

Finally, WOCE was not designed to fundamentally address the issue of "Variability". However, much was learned about this during WOCE and this new knowledge will guide the design of future climate studies (CLIVAR) and observational systems (GOOS). It is very likely that many of the scientific questions addressed but not answered by this workshop, will find their way into CLIVAR/GOOS workshops at some future time.

Appendix 1

Agenda of the Workshop

Tuesday 17th October

08:30- Registration
09:00-09:20 Opening Address

Session 1 Global Views of WOCE Variability: Data and Models
Chair: Bill Large

09:20-10:05 Variability in air-sea flux fields.
Speaker: Sergey Gulev
10:05-10:50 Satellite observations of sea surface height, surface wind stress and sea surface temperature
Speaker: Dudley Chelton
10:50-11:10 Introduction of posters (10)
(Banks, Josey, Joyce, Kubota, Large, Leeuwenburgh, Stammer, Suzuki, Swift & Webb)
11:10-13:00 Poster Session with coffee.

13:00-14:30 Lunch

Session 2 Principal Mechanisms for Variability
Chair: David Webb

14:30-15:15 The state of the atmosphere during WOCE.
Speaker: James Hurrell
15:15-16:00 Towards better interpretation of oceanic variabilities: Stimulus, response and feedback.
Speaker: Kimio Hanawa
16:00-16:10 Introduction of posters (5)
(Danabasoglu, Dobroliubov, Killworth, Webb, & Yang)
16:10-17:30 Group photo and poster session with coffee

18:30- Icebreaker

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Wednesday 18 October

Session 3 Model/data comparisons: Where are we?
Chair: Pierre-Yves Le Traon

08:30-09:15 Time-varying transports estimated by constraining numerical models with WOCE data
Speaker: Detlef Stammer
09:15-09:35 Introduction of posters (8)
(Böning, Doney, Eden, Ishikawa, Jungclaus, Komori, Tokmakian, & Yasuda)
09:35-11:30 Poster session with coffee

11:30-13:00 Lunch

Session 4 Pacific/Indian variability
Chair: Shiro Imawaki

13:00-13:45 Interannual variability in Pacific Ocean basin-scale circulation and transport during the 1990s
Speaker: Dean Roemmich

13:45-14:30 Introduction of posters (20)
(Godfrey, Aoki, Beal, Cornuelle, Van Uu, Fukasawa, Gohda, Howe, Imawaki, Isobe, Ito, Kaneko, Konda, Lee, Miyamoto, Nakamura, Peter, Shimizu, Uchida, & Uehara)
14:30-17:30 Poster session with coffee

18:30- Workshop Dinner

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Thursday 19 October

Session 5 Southern Ocean and Arctic variability
Chair: Nathan Bindoff

08:30-09:15 Temporal variability of water masses and currents in the Southern Ocean inferred from observations
Speaker: Nathan Bindoff
09:15-10:00 Arctic climate variability during the 20th century from observations and model results
Speaker: Andrey Proshutinsky
10:00-10:30 Introduction of posters (12)
(Aoki, Catchpole, Cunningham, Ikeda, Naveira-Garabato, Pokrovsky, Proshutinsky, Rintoul(2), Sokolov, Sprintall, & Yang)
10:30-12:30 Poster session with coffee

12:30-14:00 Lunch

Focus Group Discussions
14:00-17:00 (with Coffee)

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Friday 20 October

Session 6 Atlantic variability
Chair: Peter Koltermann

08:30-09:15 Atlantic variability: Messages from the past and challenges for the future
Speaker: John Gould
09:15-09:40 Introduction of posters (10)
(Azetsu-Scott, Biastoch, Dewar, Gouretski, Han, Hogg, Holliday, Lorbacher, Lumpkin, & Schott)
09:40-11:30 Posters session with coffee

11:30-13:00 Lunch

Focus Group Discussions
13:00-15:30
15:30-16:00 Coffee break

Session 7 Focus group presentations and Workshop summaries
Chair: Terry Joyce
16:00-17:30

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Session 1

Global views of WOCE variability: Data and models

Changes in the ocean: Climate change or natural variability?

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Coauthors: Richard A. Wood

Keywords: climate change, coupled model, observing systems

Recent observations have shown relatively large changes in the temperature and salinity of intermediate water masses in the ocean on decadal timescales. We compare the observed changes with modelled changes from simulations of the coupled climate model HadCM3. The observed changes in the Southern Ocean are consistent (in terms of the pattern and magnitude) with anthropogenic forcing of climate. In addition, the observed changes cannot be explained by natural (solar + volcanic) forcing and are significantly different from internal variability of the model climate system at the 5% level. By contrast, in the Northern Oceans, the coupled model suggests that changes in water masses may not be detectable for another 20-40 years.

Changes in water mass properties such as these can indicate that surface fluxes have changed. This is particularly important as it is difficult to observe changes in surface fluxes themselves because of the high level of variability. A key question is how to disentangle the signatures from heating and freshwater forcing and we are trying to understand this using coupled model experiments.

The results have important implications for the design of ocean observing systems. If a requirement of the observing system is to detect and attribute climate change, the coupled model can help us objectively decide which observations should give a high signal to noise ratio. We give an example of multi-variable detection using simulated observations from the coupled model and identify some of the oceanic variables which satisfy the criteria.

Satellite observations of sea surface height, surface wind stress and sea surface temperature

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Keywords: satellites, altimetry, scatterometry, microwave radiometry, sea surface height, wind stress, sea surface temperature

Satellites provide frequent sampling and dense spatial coverage of the surface characteristics of the world ocean. For studies of climate variability, satellite observations at microwave frequencies are most useful because they provide measurements in all weather conditions excluding rain. The ERS-1, ERS-2 and TOPEX/POSEIDON microwave altimeters have measured sea surface height variability since 1991. Microwave measurements of surface vector winds have also been available since 1991 from the ERS-1, ERS-2, NSCAT and QuikSCAT scatterometers. Although not available throughout the WOCE observational period, measurements by the Microwave Imager onboard the Tropical Rainfall Measuring Mission satellite have provided all-weather observations of sea surface temperature (SST) since December 1997 over the latitude range 40°S to 40°N. The rich diversity of phenomena revealed by these three satellite microwave remote sensing techniques will be reviewed, including baroclinic and barotropic Rossby waves, mesoscale eddy variability, variability of the ocean circulation on gyre scales, large-scale, low-frequency variability associated with the El Nino/Southern Oscillation phenomenon, the spatial scales and temporal evolution of the wind stress and wind stress curl fields and coupling between surface wind stress and SST in regions of strong SST gradients.

Variability in air-sea flux fields

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Coauthors: Thomas Jung, Eberhard Ruprecht

Keywords: air-sea fluxes, voluntary observing ship data, reanalyses, remote sensing

The overview of the surface flux variability will be given using voluntary observing ship data, reanalyses and satellite observations. We will quantify dominant patterns of the variability in the net heat flux, its components and momentum flux at the ocean surface and will address the issue of the reliability of assessments of climate variability in surface fluxes. Strengths and weaknesses of different flux products for the depiction of interannual to decadal scale variability in surface fluxes will be discussed. Specific attention will be paid to the possible sources of uncertainties in the variability patterns derived from different flux products (undersampling, changes in observational techniques, other time-dependent biases). Particularly, undersampling does not affect seriously basin-scale balances, but may have very profound local effects, affecting both climate means and variability patterns. We will discuss the effectiveness of different measures of surface fluxes balances and variability, such as meridional heat transport, regional balances, etc. Finally, surface flux variability during the WOCE period will be considered in the context of decadal scale and secular changes in the ocean-atmosphere surface fluxes. Some conclusions will be made concerning the reliability of the closure of regional heat and fresh water balances using WOCE hydrographic measurements and surface meteorological data.

The wind stress forcing of the ocean during WOCE: Results from an analysis of the Southampton Oceanography Centre flux climatology

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Keywords: wind stress

The wind stress forcing of the ocean during WOCE, as captured by the Southampton Oceanography Centre (SOC) climatology, is discussed with reference to the issues of representativeness and variability. The accuracy of the monthly mean SOC stresses is assessed by comparison with Woods Hole Oceanographic Institution research buoy measurements. The random error ranges from 0.004 - 0.008 N/m^2, corresponding to between 5 and 10% of the mean stress depending on which buoy is considered. The SOC fields are compared with those of the widely used Hellerman and Rosenstein (HR) climatology in the context of obtaining a representative picture of the wind forcing during WOCE. Significant differences are shown to occur both as a result of variations in the period sampled and choice of drag coefficient. The HR climatology was based on a longer period (1870-1976) than SOC (1980-1993) and was calculated using a drag coefficient which is now known to be biased high by of order 25%. The SOC stresses were calculated using a drag coefficient which has been confirmed by recent observational analyses. From the tropics to the mid-latitudes, the HR stresses and transport parameters tend to be stronger than SOC by an amount which is consistent with the difference in the drag coefficients. However, at higher latitudes this simple scaling breaks down and differences in the spatial structure of the Northern Hemisphere sub-polar gyres are found which are primarily due to differences in the state of the major atmospheric pressure oscillations. The North Atlantic sub-polar gyre is more intense in the SOC analysis than HR and this leads to a doubling in the strength of the Ekman suction. January mean upwelling velocities in this region deduced from the two datasets are 18.9 and 8.6 m/month respectively. In the North Pacific, a single large scale gyre is evident in SOC compared with two smaller gyres in HR. Our results indicate that the HR fields are not representative of the wind forcing during WOCE and should therefore be used with caution in analyses of WOCE hydrographic data. Results from an analysis of an extended version of the SOC dataset will be presented which quantify the seasonal to interannual variability in the wind driven response of the ocean for the period 1980-1997. In particular, variability in the Ekman transport across several latitudes that correspond to WOCE hydrographic sections will be discussed and related to the major atmospheric pressure oscillations.

Co-variability and non-stationarity of climate indices

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Keywords: ENSO, NAO, climate variability

Interannual and decadal climate variability is often expressed in terms of simple indices. For example, the El Nino Southern Oscillation (ENSO) is represented by the sea level pressure difference between Tahiti and Darwin. The regional response to different climate signals, such as wintertime precipitation in the southwest US or the Sahel, or high latitude, late winter SST anomalies, is often expressed as the sum of the separate responses to each climate index. Regional predictions of climate change are often based on this methodology. However, if these indices are not independent, this approach is incorrect. Furthermore, if these indices are non-stationary in their regional impact, importance of an index will depend upon the time period under which the analysis has been done and future importance of a given climate signal based on the past cannot be assured. Both of these scenarios are addressed and several indices are considered (SOI, NPI, PDO, NAO) using 100+ year atmospheric records.

Intercomparison of surface turbulent heat flux data

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Keywords: latent heat flux, sensible heat flux, satellite data, intercomparison

Recently we can use several kinds of global flux data, e.g. climatological ocean observation data, analysis data and satellite data, to understand climate variability. However, the available flux data have not been thoroughly compared with each other. Therefore, intercomparisons of different data against each other are needed to evaluate the current capability. In the present study, we carry out comparison of available products of turbulent heat fluxes, which include NWP products such as NCEP and ECMWF reanalysis data, satellite data such as J-OFURO and HOAPS data, and in situ data such as COADS and WOCE.

Seasonal to decadal variability of ocean surface fluxes

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Coauthors: Stephen Yeager

Keywords: surface fluxes, variability, annual cycle, representativeness

The ocean surface fluxes of momentum, heat and freshwater are computed globally for 40 years, ending with the WOCE years, 1991-1997. Limitations of the input data are discussed. Only the near surface fields of wind, temperature and humidity are available at high frequency (6-hourly) over the full time period. Satellite based radiation and precipitation are available monthly, but only for a limited time; 1984-1993 and 1979-1997, respectively. The SST required for the flux calculations is taken from two very different sources; the Reynolds and Smith blended SST product (1982-1997), and the evolving upper layer temperature from an ocean climate model (1958-1997). The mean annual cycles are shown to be very similar, giving confidence in the variability of the fluxes computed using either data source. The variability both of the annual mean fluxes and of the annual cycle of the fluxes is presented. This variability is used to assess how representative the WOCE years are of the past few decades, with respect to the surface fluxes.

Combined analysis of sea surface temperature and height

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Keywords: SST variability, Rossby waves

We investigate mechanisms responsible for the coupling of sea surface temperature and height. From local investigations of SST covariance decay and frequency spectra we observe substantial deviations from a first-order autoregressive process typical for large scale stochastic atmospheric forcing. On oceanic mesoscales the ocean wave field is found to have a marked impact on SST. This is observed from time-longitude plots for a broad range of latitudes in the North Pacific. Wavenumber- frequency spectra show that much of the SST variability on these scales can be associated with the first baroclinic mode Rossby waves which act on the background meridional SST gradient. Scaling arguments suggest that Ekman terms are much less important. No satisfactory explanation is found for increased eastward propagating variance in the SST at higher latitudes.

De-aliasing of global high frequency barotropic motions in altimeter observations

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Keywords: barotropic variability, altimetry, aliasing

The existence of high frequency (periods shorter than 10 days) energetic barotropic motions in the ocean is shown to lead to a large aliasing error in satellite altimetric observations. This error is most easily seen in the ‘trackiness’ of 10-day altimetric maps, and commonly attributed to orbit error. Fortunately, existing ocean general circulation models, when driven with twice-daily windstress fields, have considerable skill in predicting these motions. With improved forcing and models we can expect that in the future the alias can be largely suppressed by subtracting the model-generated high frequency fields.

Study of the CO_2 flux estimation in global ocean using satellite data

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Keywords: air-sea CO_2 transfer, global ocean

It is important to estimate CO_2 flux in knowledge of variability of CO_2 exchange in the global level. In order to determine CO_2 flux between air - sea interface, it is also important to drive CO_2 exchange coefficient, and CO_2 partial pressure (pCO_2), which can finally determine the CO_2 flux by multiplication. The CO_2 transfer velocity(exchange coefficient) at air-sea interface is determined by past various studies based on different dynamical mechanisms such as turbulence and wave breaking, which are closely related with wind speed, U_{10}, derived from satellite data. The determination of wind friction velocity u* using satellite-derived wind data will take an important role one of CO_2 flux computation. Relation between wind speed, U_{10} and wind friction velocity, u* can be presented by the relationship between non-dimensional roughness length and wave age included with all parameter (wind, wave), proposed by Suzuki et al. (1998). And subsequently we established the method of determination of CO_2 exchange coefficient based on whitecap model (Monahan

and Spillane 1984), using U_{10}-u* relationship, satellite data of NOAA/AVHRR (SST), DMSP/SSM/I (wind speed) and Levitus data from 1988 to 1992. In order to improve the interrelationship between partial pressure (pCO_2) and different physical and biochemical parameters in global sea surface water, a new empirical model has been established to correlate and parameterize pCO_2 in the mixed layer using the data from recent WOCE cruises. Meanwhile, by applying new empirical model, abundant historical nutrients ship data, Levitus data set and NOAA/AVHRR(SST), pCO_2 have been calculated. Finally study of parameterization and modelling of pCO_2 in the mixed Layer with different physical and biochemical parameters has been improved much. Consequently, we can determine global CO_2 flux distribution, multiplying with both products of global CO_2 exchange coefficient and global carbon dioxide partial pressure distributions. Finally, we will discuss the process of the air-sea CO_2 exchange in global scale, using satellite data.

Dissolved gas inventories as a guide to observing decadal-scale ocean change

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Keywords: decadal variability, intermediate water masses, dissolved gases

The spatial patterns of the inventory of a dissolved gas in subsurface water masses (the distributions of the depth integral of gas concentration between limiting isopycnals) provide clues to how the ocean acts as a reservoir for characteristics imprinted at the sea surface. As a demonstration exercise the inventories of dissolved oxygen - the most widely measured dissolved gas - in the intermediate waters of the Pacific Ocean are examined with an eye to design of an efficient program of measurements to determine subsequent decadal scale changes in gas inventories and, potentially, the imprint of other decadal-scale changes upon the mid-ocean.

Ocean variability in the OCCAM global ocean model

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Keywords: heat transport, fresh water transport

During the WOCE period high resolution ocean models have reached the stage where they can provide quantitatively useful information on the variability of the ocean and the mechanisms involved. In this poster we summarise the variability of the OCCAM model during two runs, one forced by climatological monthly winds and one by six-hour ECMWF winds.

The main results concern the meridional heat and fresh water transports in the different oceans split into their different components. Results are also presented on the variability in the Indonesian Throughflow and the Bering Strait and Drake Passage Transports. The Bering Strait appears to be dominated by local winds and sea level difference between the Pacific and the Arctic. At periods of more than a few months the Indonesian Throughflow is dominated by Sverdrup Balance in the South Pacific. In contrast the main variability in the Drake passage transport appears to involve a chaotic, possibly eddy driven, process.

Session 2

Principal mechanisms for Variability

Eulerian and eddy-induced meridional overturning circulations in the Tropics

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Coauthors: James C. McWilliams

Keywords: eddy-induced, Eulerian, tropical circulation, model, observations

Inspired by recent measurements of the eddy-induced meridional overturning circulation in the Tropical North Pacific Ocean by Roemmich & Gilson (2000), we analyze an Oceanic General Circulation Model for its Eulerian and eddy-induced meridional overturning circulations throughout the Tropics. The model representation for the eddy-induced circulation is the parameterization by Gent & McWilliams. The eddy-induced circulation is similar in all Tropical basins. It has a strength of about 10% of the Eulerian (Ekman) circulation, and its contribution to the meridional heat flux is a similar fraction. Its pattern is one of double cells in the vertical and antisymmetry of the meridional streamfunction about the equator. Near the equator there is downwelling above the undercurrent and upwelling below, with the return circulations closed within the upper 250 m and ±5° of latitude. Off the equator there are overturning cells in the opposite sense in each basin that reach deeper into the main pycnocline. As with the Eulerian meridional overturning circulation, the seasonal cycle in the eddy-induced circulation has a magnitude comparable to the time-mean circulation, though for an entirely different dynamical reason associated with seasonal changes in the buoyancy field. Substantial changes also occur during ENSO. The rather good agreement between the measurements and the model solution gives support to the theory underlying the parameterization of eddy-induced circulation.

North Atlantic water mass structure and modes of the meridional overturning circulation

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Keywords: North Atlantic variability, water mass, meridional overturning circulation, heat transport

A set of repeated latitudinal sections along roughly 24°N, 36°N, 48°N and 59°N is utilised to describe the interannual and interdecadal changes of the deep water characteristics of the North Atlantic during last 35 years. Changing characteristics of the Denmark Strait Overflow water (DSOW), Iceland-Scotland Overflow Water (ISOW), Gibbs Fracture Zone Water (GFZW) and Labrador Sea Water (LSW) are related to the varying intensity of the Meridional Overturning Circulation (MOC) and Meridional Heat Transport (MHT). During 1990s GFZW and ISOW were subjected to profound freshening, DSOW became warmer (0.2-0.3°C) and slightly fresher over the whole northern part of the North Atlantic. The most intensive changes were observed in the Labrador Sea Water. Cooling (up to 0.5-0.6°C) and freshening of the LSW was detected since 1960s up to mid 1990s. This process was accompanied by the increase of the LSW layer thickness and density. The opposite tendencies of the LSW core changes were observed from 1994 in the Newfoundland Basin and from 1998 in Eastern European Basin. The inconsistency in the LSW behaviour at different basins is contributed to different spreading time of the LSW from the formation region to certain locations.

Two scenarios of MOC interaction with deep circulation of the North Atlantic are suggested. These scenarios indicate that the development of MOC is governed by the changing transport of the deep waters of the Arctic origin. The suggested MOC in a single meridional cell, typical for the early 1980s and late 1990s, shows an intensive MHT (20-40% higher than the climatic mean), strong DSOW transport and reduced LSW and ISOW discharge. For the 1950s and the early 1990s we found a two-cell meridional overturning circulation with a reduced northward MHT, a strong northward advance of Antarctic Bottom Water and reduced contributions from the DSOW coincide with an increased LSW discharge to the south at lower depths and density levels. Late 1990s revealed new transition from the two-cell meridional circulation to

one-cell case with increased meridional overturning circulation and northward heat transport up to 20% in 1999 comparing with mean values for the 1990s.

The Labrador Sea Water seems to be an important part of the feed-back of the North Atlantic MOC system. Reduced production of LSW supports MOC intensification, providing plausible conditions for deep convection in the Labrador Sea by bringing salty waters to high latitudes. Active formation of LSW slows down the MOC, thus limiting the supply of salty waters needed to maintain the convection processes. The intensification of the LSW formation may be the reason of the positive anomaly of mass transport within the Denmark Strait and additional inflow of freshened waters from the Greenland Sea providing negative feedback to the convection conditions in the Labrador Sea. Climatic changes of the LSW were also related to large-scale atmospheric patterns such as North Atlantic Oscillation index (NAO), wind field vorticity variability.

Toward better interpretation of oceanic variabilities: Stimulus, response and feedback

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Keywords: North Pacific STMW, Kuroshio, teleconnection

The ocean is ceaselessly fluctuating with various time scales, regionally and globally. In order to properly understand these fluctuations and underlying mechanisms, we have to know the atmospheric forcing fields (stimulus), variations of the oceanic state (response) and their mutual interaction (feedback). From the view point mentioned above, I would like to try to interpret the variabilities of North Pacific subtropical mode water (NPSTMW) as an example of the oceanic variations.

Time series of core layer temperature (CLT) of NPSTMW for the period of 40 years from 1957 to 1996 is constructed using all available temperature profiles archived in WOD98. CLT is defined as the temperature of the layer having the minimum vertical temperature gradient at a single profile with temperature ranging from 15 to 19°C. Annual mean CLT is calculated using all CLT data taken from April to December for four 5 x 10 degrees (lat. x lon.) regions from 30°N to 35°N and from 140°E to 180°E. CLT time series shows decadal to interdecadal variation as well as interannual variation, and correlates very well with that of wintertime sea surface temperature in the same region. Relationship is investigated among several atmospheric circulation indices (such as SOI, MOI and NPI), the Kuroshio transport in the sea south of Japan and CLT. As a result, it can be concluded that CLT is crucially influenced by the Kuroshio transport in decadal time scale, and by the wintertime East Asian Monsoon in interannual time scale. In addition, the Kuroshio transport well correlates with NPI with time lag of 5 years (NPI leads the Kuroshio transport). Further, it is suggested that SST in the formation area of NPSTMW can affect the atmospheric circulation field subsequently.

The state of the atmosphere during WOCE

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Keywords: climate variability, teleconnections, ENSO, annular modes

The state of the atmosphere during the WOCE period of the 1990s was characterized by pronounced deviations from the long-term mean conditions over both hemispheres. Over the Northern Hemisphere, the dominant patterns of atmospheric variability tended to remain in one phase such that sea level pressure was lower-than-average over the middle and high latitudes of the North Pacific and North Atlantic oceans, as well as over much of the Arctic, while it was higher-than-average over the subtropical oceans, especially the Atlantic. Moreover, in the past 30 years, trends in these leading patterns of variability appear to be unprecedented in the observational record. Over the Southern Hemisphere, similarly remarkable changes have been documented in the leading pattern of variability such that SLP during the 1990s was anomalously low over the high latitudes and anomalously high over the subtropics. These changes in atmospheric circulation have led to stronger-than-average westerlies over the middle latitudes of both hemispheres. Over the tropics, the Southern Oscillation persisted in a strong negative phase during most of the WOCE period, reflecting higher-than-average (lower-than-average) surface pressure over much of the western (central and eastern) equatorial Pacific with weakened tropical easterlies.

The large-scale anomalies in the atmospheric circulation during the WOCE period are strongly related to variations in modes of natural variability. The temporal behavior of these leading modes will be examined, placing the WOCE period into a longer-term perspective.

Vertical normal mode decomposition of propagating disturbances

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Keywords: planetary waves, propagation, disturbances, variability

Propagating features and waves occur everywhere in the ocean. This paper creates a fairly accurate descriptor of how such small-amplitude, large-scale oceanic internal disturbances propagate. For a flat-bottomed ocean, assumed here, the linear internal modes form a useful basis for expanding the oceanic shear modes of propagation. Remarkably, the shear modal structure is largely independent of orientation of the flow. The resulting advective velocities, which we here term pseudovelocities, comprise background flow decomposed onto normal modes and westward planetary wave propagation velocities. The diagonal entries of the matrix of pseudovelocities prove to be reasonably accurate descriptors of the speed and direction of propagation of the shear modes. The first shear mode is dominated by westward propagation, and possesses a mid-latitude speed-up over the undisturbed linear first mode planetary wave. The pseudovelocity for the second shear mode, in contrast, while still dominated by westward propagation at lower latitudes, shows a gyre-like structure at latitudes above 30°. This resemble in both shape and direction the geostrophic baroclinic flow between about 500 and 1000 m depth, but are much slower than the flow at these depths. Features may thus be able to propagate some distance round a subtropical or subpolar gyre, but not in general at the speed of the circulation.

On the region of large SSH variability in the Southeast Pacific

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Keywords: Pacific Ocean, sea-level variability

Satellite Altimeter observations of sea surface height show an extensive triangular region of high variability in the Southeastern Pacific. The region is unusual in two ways. First it appears to have a horizontal correlation scale which is much large than that associated with the mesoscale eddy rich regions of the deep ocean. Secondly the feature appears to reflect the shape of the underlying topography. We investigate the phenomena using the emperical orthogonal function technique to data from a high resolution global ocean model forced by 6-hourly winds from the ECMWF reanalyzed data set. The investigation indicates that the variability is primarily a trapped barotropic response to high frequency variations in the surface Ekman forcing. The results show that nearly 30% of the SSH variability of the region is associated with the lowest breathing mode and that there is a delay of about two days between the maximum Ekman forcing and the fastest change in SSH.

Indonesian Throughflow: An Indo-Pacific teleconnection mechanism for climate changes

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Keywords: Indonesian Throughflow, Kelvin and Rossby waves, sea-level variation

Observations indicate that the transport of Indonesian Throughflow varies considerably from intraseasonal to interannual time scales. It has been postulated that some of such variations are related to changes in the upstream regions, such as near the western boundary in the tropical Pacific Ocean. In this study, we analyze the sea-level data from TOPEX/POSEIDON (T/P) altimeter, and results from a simple ocean model to investigate this Indo-Pacific connection and its impact on the Southern Indian Ocean. It is shown that the radiation of Rossby-waves, as forced by coastal Kelvin waves originated from the western tropical Pacific Ocean, plays an important role for sea-level changes in the southern Indian Ocean. Thus the throughflow is a potentially important mechanism for connecting variations between the Pacific and Indian Oceans.

Session 3

Model/data comparisons:
Where are we?

Seasonal variability of deep currents in the equatorial Atlantic: A model study based on DYNAMO and FLAME

Claus Böning

Modeled and observed seasonal to decadal oceanic variability

Scott C. Doney

Mechanisms of interannual to decadal variability in models of the North Atlantic Ocean

Carsten Eden

Kuroshio path variation in a high-resolution North Pacific Ocean Model

Ichiro Ishikawa

Simulating North Atlantic ocean variability in an OGCM

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Regional ocean state estimation for the Kuroshio south of Japan

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Time-varying transports estimated by constraining numerical models with WOCE data

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The ocean’s variability as seen by models and observations, a study at 24°N

Robin Tokmakian

Decadal variability of the North Pacific upper ocean

Tamaki Yasuda

Seasonal variability of deep currents in the equatorial Atlantic: A model study based on DYNAMO and FLAME

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Keywords: equatorial circulation, seasonal variability of deep currents

Recent measurements with moored current meters across the Deep Western Boundary Current (DWBC) and in the vicinity of the Romanche Fracture Zone have revealed a significant seasonal variability in the deep current fields near the equator. Here we use a host of experiments with different eddy-permitting models of the Atlantic Ocean (partly from the EU-project "DYNAMO" and partly from a recently developed "Family of Atlantic Model Experiments" [FLAME]) to demonstrate that

- the patterns of seasonal current variations in the deep equatorial Atlantic are a robust feature of different numerical models;
- the model results quantitatively reproduce the observed current variations;
- the locally observed current variations are part of a basin-wide system of eastward and westward current bands driven by the seasonal wind oscillations over the equatorial wave guide;
- the interaction of the zonal current bands with the DWBC gives rise to a complicated pattern of seasonal recirculation cells near the western boundary, so that
- transport measurements of the DWBC not extending across these cells are not representative of variations of the net meridional transport near the western boundary.

Modeled and observed seasonal to decadal oceanic variability

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Keywords: hindcasting, oceanic variability, SST, sea level

A method for hindcasting seasonal to decadal oceanic variability is presented, for the purpose of investigating how the magnitude, spatial patterns and timescales of this variability compare with observations. A key element is the atmospheric reanalysis data, which provides global 6-hourly winds, air-temperature and near surface humidity from 1958 to the present. With these fields the wind stress, the sensible and latent heat fluxes and the evaporation used to drive an ocean climate model should have realistic variability on seasonal to decadal time scales. However, the satellite data required for the radiation, and precipitation forcing are not available for the full 40 years. Features of the mean state of the model and its drift, that may significantly influence interpretation of the variability are discussed. The simulated seasonal cycles and interannual to decadal variability of surface and subsurface temperature and salinity fields, ocean circulation, and sea-level height are shown. These historical simulations are evaluated against hydrographic data sets spanning the full time range and satellite SST and TOPEX sea level data covering approximately the final one to two decades of the simulation. It is argued that the model—data comparisons should sometimes be viewed as a joint evaluation of imperfect records. Overall, the results demonstrate that a substantial fraction of the observed interannual to decadal oceanic variability can be reconstructed by forcing with the surface atmospheric reanalysis data. This may arise either because the ocean is indeed simply responding to atmospheric forcing or because the atmospheric record already reflects coupling and feedbacks from the ocean; with reality likely somewhere in between.

Mechanisms of interannual to decadal variability in models of the North Atlantic Ocean

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Keywords: heat transport 48°N, ocean response to NAO

Hindcast experiments of the last decades with non-eddy resolving and eddy permitting FLAME models were performed. They show that the bulk of the variability of northward heat transport at 48°N in the Atlantic Ocean is related to the NAO. The fast barotropic (intraseasonal) and the delayed (interannual) response of the North Atlantic to NAO-type changes in wind stress and heat fluxes changes the midlatitude to subpolar heat content in a way that atmospheric baroclinicity is first enhanced (fast response) and reduced afterwards (delayed response) which rises the possibility of a coupled feedback loop between ocean and atmosphere. Comparison of the model results with TOPEX/POSEIDON SSH data show that the interannual changes in the heat content in the North Atlantic and therefore oceanic heat transport are in good agreement with observation.

Kuroshio path variation in a high-resolution North Pacific Ocean Model

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Coauthors: Hiroshi Ishizaki

Keywords: Kuroshio, high-resolution model, North Pacific

Interannual Kuroshio path variation which occurs in a high-resolution North Pacific Ocean Model driven by climatological annual forcing is presented. The model is a z-coordinate free-surface OGCM with the Generalized Arakawa scheme for momentum advection. Horizontal resolution is 1/6° in the latitudinal and 1/4° in the longitudinal direction, with 44 vertical levels. Integration is carried out for 100 years, including the initial restoring body forcing of temperature and salinity to the observed state for the first six years.

Results show realistic Kuroshio paths, including separation of the Kuroshio off Boso Peninsula. During the experimental period, Kuroshio path transitions from large-meander to non-large-meander can be seen three times (the same for reverse transitions). Each non-large-meander period lasts for a couple of years, and corresponds to the period when transport through the Tokara strait is relatively small, which is consistent with observations. The present results suggest that nonlinearity may be one of causes for interannual Kuroshio path variation.

The results from ongoing experiments by forcing with interannual change will be also presented.

Simulating North Atlantic ocean variability in an OGCM

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Keywords: OGCM, North Atlantic, NAO, thermohaline circulation

On interannual to interdecadal timescales the North Atlantic responds to variations in large-scale atmospheric features. Examples are the observed correlations between the North Atlantic Oscillation (NAO) and the properties of the Labrador Sea Water (LSW) or variations in the meridional heat fluxes. Moreover, the NAO triggers the relative importance of the deep water formation sites to the south (Labrador Sea, LS) and to the north (Greenland-Iceland-Norwegian Sea, GIN) of the Greenland-Scotland Ridge (GSR). A new version of the C-Grid Hamburg Ocean Primitive Equation model (C-HOPE) is used to study the ocean's response to realistic atmospheric forcing. The global ocean model features an embedded dynamic-thermodynamic sea ice model and, owing to the conformal mapping technique, allows for varying horizontal resolution. The model is forced with daily data from the NCEP reanalysis project for the period 1948-1999. As well as in the LS the model is able to produce a substantial portion of the deep water in the GIN sea. In particular, a sensitivity of the convective activity in the respective deep water production areas to the NAO phase was found on decadal time scales. During NAO - high phases (e.g. mid 1970s to 1990s) the convection is intensified in the LS and weakened in the GIN sea, vice versa during NAO - low periods (1950s to 1960s). The formation rate of LSW is strongly related to the intensity of wintertime deep convection and determined by the local surface conditions. The simulated LS convection reproduces the main characteristics of the observations. Anomalies spread out into the North Atlantic and modulate the upper North Atlantic Deep Water (NADW). The deeper layers of the NADW are fed by the dense overflows over the GSR and are therefore less directly linked to the GIN sea convection. However, the simulations suggest that the overflow properties and the sources of overflow waters vary on decadal timescales too.

Regional ocean state estimation for the Kuroshio south of Japan

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Keywords: Kuroshio variability, TOPEX/Poseidon altimetric data, ADCP data, variational data assimilation

Observations so far have revealed that the Kuroshio, which is the western boundary current of the subtropical gyre in the North Pacific, shows significant path variabilities around Japan and that the variabilities provide a great impact on the mass and heat exchange between the subtropical and subpolar gyres. To progress our understanding of the detailed physical processes of the Kuroshio path variabilities and the resulting mass and heat exchange with the surrounding regions, good oceanographic reanalysis data sets with high resolution in space and time are required. However, it is difficult for the present observational system to provide such data sets because the resolution is still coarse.

In this study, to construct the regional ocean state estimation for the Kuroshio around Japan, we carry out several prediction experiments of the Kuroshio path variation by assimilating the TOPEX/Poseidon altimetric data and ADCP data into a regional 1 1/2-layer primitive equation model with 1/12° grids. Because nonlinear effects are quite significant in the western boundary current regions, variabilities of the currents highly depend on the dynamics of themselves rather than external forcing. Thus good initial conditions are essential for success in the prediction of the Kuroshio path variations.

Firstly, using the variational initialization scheme exploited by Ishikawa et al. (2000), which contains the dynamical constraint that works as the low-pass filter, we have performed several identical twin experiments in order to confirm the efficiency of our variational assimilation model for the initialization of the short-range numerical forecasting of the Kuroshio path variations in the case of the realistic geometry. Comparison with

the result initialized by the classical optimal interpolation scheme (OI) showed a drastic improvement in accuracy of both initialized velocity and vorticity fields. For example, the rms errors of the velocity and vorticity fields reduced approximately by 35% and 50% compared with those by OI, respectively.

Then, using the sea surface dynamic height data derived from the TOPEX/Poseidon altimetry by Kuragano and Shibata (1997) and ADCP data south of Japan, we have carried out the 5-year hindcast experiments of the Kuroshio path variation from 1993 with particular emphasis on 1) transition from a straight to a meandering path, 2) a meandering-path state, 3) transition from a meandering to a C-type path, and 4) a straight-path state. Although we used a mean field of the 5-year simulation as a background field of initialization for all experiments, the Kuroshio path variation has been successfully reproduced to the extent of two months after initialization. In particular, the eastward progression speed and the amplitude of the Kuroshio meander were quite similar to those observed.

Time-varying transports estimated by constraining numerical models with WOCE data

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Keywords: general circulation, data assimilation, numerical modeling

The ultimate goal of WOCE and now CLIVAR is to constrain ocean circulation models by large-scale and global data sets and to use the resulting simulations of the time-varying flow field to study the ocean and its consequences on climate. A pre-requisite for such an ocean state estimation is a careful comparison of circulation models with the WOCE data set to assure consistency between both and to guide the improvement of circulation models.

In this talk we will summarize comparisons of state-of-the-art circulation models with various WOCE data sets. We will then proceed by describing details of a global optimization that makes use of various global data set. An overall description of the estimated mean state will be presented. We will test the results through a comparison with the independent information available from large-scale WOCE data sets, including the global one-time hydrography, the global XBT data set, surface drifters and deep ALACE floats. The implication of the estimated state for oceanic transports and major transport pathways will be analyzed subsequently.

The ocean’s variability as seen by models and observations, a study at 24°N

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Keywords: ocean model, variability, HOT, heat transports

The variability in ocean models shows a rich variety of temporal scales in its physical structure. This paper takes a small spatial sample (a zonal section along approx. 24°N) of a 20 year simulation at relatively high resolution (Parallel Ocean Climate Model or Semtner and Chervin Ocean Model, 1/4 degrees) and explores the realism of the low frequency signal (seasonal to interannual) in the surface, intermediate and deep waters. The variability seen in data, for example, from the HOT experiment, are compared with the model’s variability of these water masses. The 4D model fields are used to explore the possible reasons for the variability, which in some cases, appear as wave-like features. The changes in the meridional heat transport is also discussed in light of the variability seen across the basin in the vertical structure as computed by the model. Comparisons are shown for both the Pacific and Atlantic basins. The model, forced with realistic winds, heat fluxes, and freshwater fluxes (ECMWF) provides an opportunity to explore the relationships between various parameters and allows in situ time series at a single point to be placed into the context of a four dimensional field.

Appendix 2.S3

Decadal variability of the North Pacific upper ocean

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Keywords: North Pacific, decadal variability, OGCM

Decadal variability of the North Pacific was simulated by an ocean general circulation model of Meteorological Research Institute. The ocean was driven by historical data of monthly wind stress and atmospheric parameters from 1960 to 1993. We analyzed the results focusing on the oceanic role on the coupled decadal variability, i.e., the movement of the subduction signal from mid- to low- latitudes. Furthermore, model results were compared with those along the repeated hydrographic sections conducted by Japan Meteorological Agency.

Temperature change in the mixed layer in the central North Pacific was caused by the divergence of the heat transport in the surface Ekman layer, in addition to the surface heat flux. Decadal temperature anomalies were found to subduct in the central North Pacific: the positive anomalies in 1972-1976 and 1989-1993, and the negative in 1978-1988. Although those subducting anomalies reached 20°N along the subtropical gyre, we could not trace them to the equator. In another simulation with the wind stress anomalies south of 20°N eliminated, the subducting temperature anomalies weakened and extended to the western tropical North Pacific, so that they diffused out before reaching the equator. The observed tropical temperature variations along 137°E were consistent with those simulated for both interannual and interdecadal time scales. For longer than the ENSO time scale, the negative anomalies appeared in the 1960s, the positive in the 1970s, and negative in the late 1980s and the early 1990s. It was concluded that temperature anomalies in the western tropical North Pacific between 5-15°N were mainly determined by the zonal propagation of the Rossby waves generated by the wind stress curl.

Session 4

Pacific/Indian variability

Subsurface subtropical fronts of the North Pacific as boundaries in the ventilated thermocline
Yoshikazu Aoki
Monsoon variability at 8.5°N in the Arabian Sea
Lisa M. Beal
Climatologies and variability from the WOCE high-resolution XBT network in the Pacific
Bruce D. Cornuelle
Changes in bottom sea water property observed through SAGE P1 revisit
Masao Fukasawa
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Subsurface subtropical fronts of the North Pacific as boundaries in the ventilated thermocline

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Keywords: ventilated thermocline, subtropical front, potential vorticity

An eastward upper flow in the central subtropical gyre of the North Pacific and an accompanying subsurface temperature/density front have been documented by many authors (e.g., Uda and Hasunuma 1969), which are often referred to as Subtropical Countercurrent and Subtropical Front. While early studies suggested that this countercurrent/front could be caused by a local wind structure (e.g., Yoshida and Kidokoro 1967a,b; Cushman-Roisin 1981), Takeuchi (1984) showed that the local wind stress distribution is not essential by using an ocean general circulation model. Recently, Kubokawa and Inui (1999) and Kubokawa (1999) suggested that a low potential vorticity water subducted and advected from the northern part of the gyre can cause the countercurrent/front. In the light of these new studies, the countercurrent/front is inherently related to the structure of the ventilated thermocline. The present study attempts to document detailed structure of the subsurface countercurrent/front and clarify its significance in the ventilated thermocline and its temporal variability. Analysis of long-term repeat hydrographic sections along 155°E, 144°E, 137°E and 130°E captures two subsurface temperature/density fronts and associated eastward currents near 23°N and 18°N on the average. The northern front corresponds to the front mentioned above. While the southern front is also already noticed in literatures (Nitani 1972; Hasunuma and Yoshida 1978), the present analysis reveals that it corresponds to a boundary between lower potential vorticity (PV)/higher apparent oxygen utilization (AOU) water to the north and higher PV/lower AOU water to the south in the density range of 25.2-26.2σ_θ. It seems to mark a southern limit of the water subducted from the mid-latitude region where the deep winter mixed layer develops. On the other hand, water of far lower PV is found on the poleward side of the northern front along 25.4σ_θ surface, likely corresponding to southern bounds of the advective influence of Subtropical Mode Water. While these fronts change their positions from one cruise to another, the mean positions of the northern and southern fronts tend to shift northward gradually to the east.

The subsurface fronts corresponding to those found in the repeat hydrographic data are identified in the WOCE/WHP lines along 137°E, 149°E, 165°E and 179°E. Significant deviations from their mean positions are observed in some sections. For example, both the northern and southern fronts shift to the north in the 137°E section. On the contrary, the relevant subsurface fronts are not found in the sections along 153°W and 135°W. The absence of the fronts is reasonable because the advection of the low PV water is not expected in the eastern subtropical region according to the ventilated thermocline theory.

Since the subsurface subtropical fronts likely mark boundaries of distinct water masses in the ventilated thermocline, their changes in strength and positions probably reflect variations of the subduction processes, the gyre intensity, etc. Further analysis of the temporal variability of the fronts is now under way.

Monsoon variability at 8.5°N in the Arabian Sea

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Keywords: Indian Ocean monsoon, Great Whirl, inverse model

The northern Indian Ocean is subject to the strong seasonality of the monsoon winds and as a result exhibits remarkable variability in its circulation and property patterns. As a component of the Indian Ocean WOCE and the NOAA repeat hydrographic programs two sections were occupied in the Arabian Sea during the onset (June) and wane (September) of the 1995 southwest monsoon. Each zonal section crosses from Somalia to Sri Lanka along 8.5°N, enclosing the Arabian Sea to the north. These data provide a unique opportunity to diagnose the absolute circulation of the Arabian Sea at different stages of the monsoon cycle using an inverse model. Although the monsoon-driven ocean cannot be perceived as steady, TOPEX/ERS2 fields of sea level anomaly show that the loss of volume in the Arabian Sea over the course of the southwest monsoon is equivalent to less than -0.1 Sv crossing 8.5°N and therefore mass and property transport constraints may be rigorously applied to the two hydrographic sections. Variations in heat and freshwater transports between June and September result from a complex structure of water property changes that penetrate deep into the water column. For instance, the mixed layer deepens by over 100 m and, to the east of the Great Whirl, there are significant increases in salinity on isopycnals from the surface down to depths of 1500 m. In the Great Whirl itself waters are cooler and fresher in September reflecting their southerly source and the vortex doubles in diameter to over 450 km across. Moreover, direct velocities from Lowered ADCP indicate that while the Great Whirl is trapped in the mixed layer in June, by September the circulation penetrates to a surprising 3000 m depth and, as a result, its transport increases ten-fold from 10 to 100 Sv, with a net northward transport in each case of about 10% its magnitude.

Climatologies and variability from the WOCE high-resolution XBT network in the Pacific

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Keywords: climatology, interannual variability

The World Ocean Circulation Experiment (WOCE) repeated high-resolution expendable bathythermograph (HRXBT) network in the Pacific is used as the basis for climatological analyses. The network presently consists of 7 sections, spanning the Pacific basin, which repeat the same Volunteer Observing Ship tracks approximately every 3 months. A technician or scientist is accommodated on board the ship in order to sample around the clock using an automatic XBT launcher. Precise XBT locations are controlled by GPS navigation. Temperature sampling is to 800 m using Sippican Deep Blue XBT probes. Expendable conductivity and temperature profiler (XCTD) profiles are taken by the observer at key locations to supplement the historical T-S relations. Over 1300 XBT profiles are obtained from each repeat of the network. Sampling begins and ends near the shelf break in waters between 100 and 200 m depth. Probe spacing is as large as 50 km in mid-ocean quiet areas, increasing near boundaries, the Equator, islands, and other regions of enhanced variability to a maximum of about 10 profiles per degree. The sampling is designed to capture most of the variance associated with mesoscale features and boundary currents. The first HRXBT sampling began in 1986, with new sections started in 1991, 1993, and 1997.

The HRXBT sections with at least 7 years of data are used to estimate the seasonal march of temperature, heat content, and steric height. After removal of the seasonal march, the residuals are smoothed in time to separate the mesoscale variability from the interannual variability in the sections. The residuals show many examples of persistent small-scale structure, including horizontal variations in the annual cycle. Computing the covariances and correlations between points on the sections show significant non-local and small-scale features in both the correlations and the EOFs used to decompose the horizontal variability. These statistics can be used to compare to model simulations and as simple checks on surfacing forcing climatologies.

Appendix 2.S4

Changes in bottom sea water property observed through SAGE P1 revisit

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Keywords: P1 revisit, deep/bottom water change, SAGE

SubArctic Gyre Experiment (SAGE), an ocean research program funded by STA, carried out P1 revisit cruise under a collaboration with IOS and Princeton Univ. in 1999. P1 was occupied in 1985 by US WOCE. In the revisit cruise, SAGE occupied 105 stations in the west of 145°W. Most of revisited stations were located just on stations of P1 and cross points with other WHP lines. Objectives of the observation were; (1) to detect how deep the surface sea water properties penetrate during these 14 years using transient tracers as freons, SF6 and DIC, (2) to detect changes in the sea water property at mid and deeper depths, and (3) to collect data of radio active carbons to depict the deep overturn in the subarctic North Pacific.

Our result shows marked changes in sea water property or in T-S relations at depths shallower than 500 m and at depths within 1000 m from the bottom. As for changes at the shallower depths, they show zonal structures and seem to be attributed to the oceanic regime shifts which took place at these latitude in 1980s and late 1990s. On the other hand, changes at the bottom 1000 m layer are the warming and the freshening without a zonal structure within SAGE area. Also the decrease in DO was found at the bottom layer. These features of changes at the bottom layer were also recognized at cross-points with P13, 15, 16, 17, respectively. The mixing of the bottom water with the deep water in the northern North Pacific seems to be enhanced during this decade, or, changes in the bottom water with much longer time scale might be observed.

The role of seasonal and intraseasonal stress variations in generating long-term mean heat flux into the Indian Ocean

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Keywords: overturning cell, heat transport, air-sea coupling, Intraseasonal Oscillations.

In boreal summer, more water is upwelled and warmed north of the equator in the Indian Ocean than can be removed by the (well-defined) annual mean Ekman transport across the equator; this latter is the annual mean of
$(\rho\beta)^{-1} d\tau_x / dy$ integrated across the Indian Ocean at the equator — closely related to the Sverdrup transport. A numerical model experiment has been designed to explore the fate of this summer excess upwelling. In a control run, a global ocean circulation model is forced with observed monthly mean shortwave radiation, wind speeds, air-sea humidity ratios and wind stresses. In the experimental run, the wind stresses (only) are replaced by their 12-month running mean (12MRM). 12MRM inter-run differences in downward surface heat flux and SST have a ratio of about -10W/m^2/°C in the tropics, much as expected from the fact that shortwave radiation, surface wind speeds and humidity ratios are the same in the two runs. SST rises as much as 2.5°C off Somalia in the experiment compared to the control, due to reduced coastal upwelling. 0-100 m velocity differences might be expected to be in thermal wind balance with the 0-100 m average temperature; in fact they flow down a strong gradient of this average temperature, to accelerate and cross the equator near Africa in a shallowing of the cross-equatorial “Southern Gyre”. They then join a strong eastward (difference) equatorial jet, thus removing the warmer Somali SSTs eastwards.

The 12MRM net heat flux into the Indian Ocean north of 7°S reduces (in the model) by 6 W/m^2. The Indonesian Throughflow and western boundary inflow become shallower and warmer, and the (southward) Sverdrup outflow across 7°S becomes deeper and colder in the experiment compared to the control run. The net effect is a reduction of the overturning cell, resulting in the 6 W/m^2 reduction in surface heat flux. At least some of the change in vertical mass transport (and water mass change) seems to occur in the eastern equatorial Indian Ocean, perhaps due to removal from the experimental run of low Richardson numbers associated with the transient Wyrtki Jets. If so, it suggests that the causes of change in area-average SST and heat flux in the northern Indian Ocean may lie as much in mixing in the eastern Indian Ocean as in the Somali Current system.

Loschnigg and Webster (pers comm) have recently examined response of an ocean model to daily (rather than monthly mean) forcing. The amplitude of effects due Intraseasonal Oscillations (suppressed on monthly forcing) are comparable to amplitudes of the mean seasonal cycle. Thus the changes in annual net heat flux described above may be substantially larger than those described above, if a model run with full diurnal forcing is compared to one in which diurnal wind stresses are replaced by their annual mean. Composites of ISO events (Webster, pers comm) show them to be part of a strongly coupled ocean-atmosphere phenomenon.

VOS ADCP observation of surface current of the western Pacific

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Keywords: western Pacific, surface current variability, ADCP repeated survey

The western Pacific ADCP monitoring program started in 1996 as part of JGOOS. Now the Fundamental Strategy Program of Japan Science and Technology Corporation support this program during October 1997 to September 2002. In this program surface currents along a line between Japan and Australia are repeatedly surveyed by a volunteer observing ship (VOS). The 150 kHz RDI-BBADCP is mounted on the hull of the mineral transport ship (83658 tons in weigh and 289 m in length), named ‘First Jupiter’. Total 23 cruises done at present. Variability of the currents are presented.

Decadal differences in the deep Indian Ocean water masses from 1960s to 1980s

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Keywords: Indian Ocean, decadal change, Antarctic Intermediate Water, Subantarctic Thermocline Water

Decadal differences in the deep Indian Ocean water masses were inferred from past and modern hydrographic data. The historical data set compiled by Reid and Mantyla over many years and from many cruises was compared to the WOCE I3 and I5P sections taken in 1995 and 1987. The historical data were collected mostly in the late 1960s, with a standard deviation of about 11 years. The mean year of these data is 1970. The data were vertically interpolated to neutral surfaces (Jackett and McDougall, 1997), rather than being compared on isopycnals, to eliminate ambiguities associated with choosing reference pressures for potential density.

Historical salinity, temperature, pressure and oxygen data were mapped using objective methods to the coordinates of the WOCE hydrographic sections. Comparisons between the historical and modern data were then made along the neutral density surfaces. It was found that there are significant basin wide changes in the three main water masses represented in I3 (at a latitude of approximately 20°S) : thermocline waters, Antarctic Intermediate Water (AAIW) and Upper Circumpolar Deep Water (UCDW). The waters of the main thermocline were found to show a decrease in temperature and salinity on neutral density surfaces. For example, the zonally averaged temperature decrease along the neutral density 26.9 kg/m^3 was approximately

0.45°C, and the zonally averaged salinity decrease along that surface was approximately 0.12 psu. The salinity minimum of AAIW showed a decrease in temperature and salinity on density surfaces. The zonally averaged temperature decrease along the neutral density 27.5 kg/m^3 was 0.05°C, and the average salinity decrease along that surface was approximately 0.02 psu. The salinity maximum of the UCDW water mass was found to have increased in temperature . The pressure surfaces did not show coherent spatial trends. An oxygen minimum was found in the main thermocline waters. A weak oxygen decrease of approximately 10 micromol/kg was found along neutral density 26.9 kg/m^3. Overall, these results are consistent with observed differences reported at 32°S (Bindoff and McDougall, 2000).

The differences in internal water mass properties are assumed to result from changes in the surface conditions at their formation regions. These results are consistent with the scenario of freshening of waters in high latitudes (the source of AAIW), and warming and possible salinity increase of low latitude waters (source of the thermocline water mass).

Seasonal signal of the Kuroshio transport south of Japan estimated from in situ oceanographic data and satellite altimetry data

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Keywords: Kuroshio, transport, seasonal signal, altimetry data

The Affiliated Surveys of the Kuroshio off Cape Ashizuri (ASUKA) Group carried out oceanographic observations along a line crossing the Kuroshio south of Japan, which was chosen to coincide with a sub-satellite track of the altimeter satellite TOPEX/POSEIDON. From October 1993 to November 1995, they maintained moored current meters and carried out repeated hydrographic sections. From those in situ data, geostrophic velocities normal to the observation line are estimated, referring to velocities observed at mid and deep layers, for 25 cases. From those velocities, the volume transport of the Kuroshio (transport of the entire eastward flow) for the upper 1,000 m is estimated. The transport is found to be proportional to the sea level difference across the Kuroshio.

Having this relationship and using TOPEX/POSEIDON altimetry data, a time series of the Kuroshio transport is obtained for seven years (1992-1999). The result shows large fluctuations around an average of 57 Sv (1 Sv is million cubic meters per second). Most of the fluctuations are associated with fluctuations of both the stationary and propagating eddies superimposed on the Kuroshio system. Eliminating the transport associated with those local recirculations, the transport of the Kuroshio as a throughflow is estimated. The result shows smaller fluctuations around an average of 42 Sv.

The seasonal signal in the observed transport is small compared with the transport of western boundary current expected from the interior Sverdrup transport at mid-latitudes estimated on the basis of observed surface wind field (re-analysis data of the National Centers for Environmental Prediction). There may be some seasonality, however, that it is low in September and high in December, similar tendency as the theoretical transport. The observed interannual fluctuation is compared with fluctuation of the geostrophic (baroclinic) transport of the Kuroshio obtained along the 137°E meridian.

Seasonal transport variation of the Kuroshio in the two-layer numerical model with a ridge

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Keywords: seasonality, Kuroshio volume transport

A two-layer numerical modeling forced by the wind stress is carried out to identify the baroclinic activity amplifying the annual variation of the Kuroshio volume transport. Special attention is given to the effect of a ridge, mimicking the Izu-Ogasawara Ridge, on the generation of the baroclinic activity through the coupling of the barotropic and the baroclinic modes of motion. When the annual variation is concerned, the lower-layer motion remains in areas surrounding a ridge because the isostasy (a state of the motionless in the lower layer) is not achieved within such short timescale. Thus, the lower-layer flow impinges on the bottom slope. Such impinging process generates anomalies of the upper-layer thickness especially on the eastern side of the ridge. Thereafter, anomalies move westward with characteristic velocities composed by the vertically averaged flow and the westward propagation of the long Rossby-wave. As anomalies of the upper-layer thickness move westward above the ridge, the isostasy is accomplished rapidly and locally with respect to the anomalies. Therefore, the positive (negative) anomaly of the upper-layer thickness has the information of the positive (negative) anomaly of the volume transport when it reaches to the western edge of the ridge. Hence, anomalies of the volume transport are released to the west of the ridge. This experiment shows that the annual range of the volume transport is amplified to about 10 Sv in the west of the ridge, and that the annual variation is mostly caused by the baroclinic activity generated on the ridge.

Characteristics of altimetry SSH anomaly of TOPEX/POSEIDON on the OICE line and its relation for geopotential height anomaly and measured velocity by a mooring system

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Keywords: Oyashio, mixed water region, SSHA, mooring

To estimate transport of the Oyashio which flows south coast of Hokkaido Japan, we set a intensive observation line along the T/P orbit 060. The observation line extends from the Cape Erimo to the southeastward (from the Oyashio region to the mixed water region) and we named this line as OICE (Oyashio Intensive observation line off Cape Erimo). On the OICE, we have been repeating CTD observations and maintaining the mooring systems. In this paper, we analysis the basic characteristics of SSHA, compare the SSHA with geopotential height anomaly and find out the horizontal scale which brings the best matching between the geostrophic surface velocity derived from SSHA and the one derived from geopotential height anomaly. The decorrelation scale of SSHA is within 50-100 km at the vicinity of the mooring point TP2 (42°21'N , 144°31'E). About 60 km Gaussian low-pass filter and the about 60 km distance brings good correlation between the geostrophic surface velocity derived from SSHA and the one derived from geopotential height anomaly. The geostrophic surface velocity derived from low-passed SSHA also has good correlation with absolute subsurface (about 400 m depth) velocity measured by the mooring system. This fact shows a possibility to monitor the velocity field from the altimetry data even in the mixed water region and the Oyashio region where the SSHA variation is not so high.

Appendix 2.S4

Interannual variability of the NPIW salinity minimum core observed along JMA's repeat hydrographic sections

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Keywords: North Pacific Intermediate Water, decadal variability, salinity minimum

We have made an analysis of interannual variability of the North Pacific Intermediate Water (NPIW) observed along JMA's repeat hydrographic sections in the western North Pacific. At 137°E, where observations have been carried out over 30 years since 1967, the long time-series of NPIW volume amount defined by salinity minimum core (S<34.2) shows clear decadal variability. A positive trend is overlapped since the minimum period in the latter half of 1970s. The amount during the maximum in 1990s is twice as large as the one during the 1970s' minimum. This increase was caused by thickening and southward spread of the core, and accompanied a decrease in the minimum salinity of NPIW. These variations at 137°E can be partly compared with the ones at 155°E and 165°E, where observations were limited in short periods. The NPIW core at 155°E was thicker and spread farther to the south during 1989-93 than 1972-77, in agreement with the change at 137°E. When the core at 165°E thickened from 1997 to 1998, the amount at 137°E simultaneously increased by 50%. This synchronism suggests that variability of NPIW core at 137°E is influenced rather by basin scale circulation over the western North Pacific than by local flow conditions. In order to elucidate its mechanism, it is necessary to investigate variations of the followings: westward recirculation of the subtropical gyre, amount of NPIW formation, and original salinity of NPIW.

The seasonal and interannual variation of the heat budget of the mixed layer in the North Pacific

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Keywords: air-sea interaction, mixed layer, North Pacific, satellite measurement

We evaluate the heat budget of the surface layer in the North Pacific from the satellite-derived surface heat flux and the numerical model velocity field, and discuss the seasonal and the interannual variability of it. The satellite-derived turbulent heat flux and the radiation flux data range from July 1987 to June 1991. The seasonal cycle of the surface velocity field which is computed by the robust diagnostic model based on Kobayashi (1999) are used together with the sea surface temperature (SST) field to obtain the lateral heat flux in the ocean. The velocity field does not change interannually to emphasize the effect of the anomalous change of the sea surface thermal condition. The heat exchange between the surface and the subsurface layer is determined by the residual of the surface and horizontal heat fluxes and the change of the heat content with the seasonal variation of the mixed layer depth. The annual cycle of the heat budget shows that the increase of the heat content is not so large in the spring in spite of the increasing SST and the heat input at the surface. The strong winter cooling at the surface is used to deepen the mixed layer, whereas the decrease of the SST is maximal in the autumn. In contrast, the interannual variability of the surface heat flux in the winter does not necessarily balance the heat content anomaly, which tends to be large in the winter due to the deep mixed layer. The heat exchange anomaly at the bottom of the mixed layer is also large, which suggests that the entrainment of the subsurface water as the reminder of the heat budget in the summer may affect the interannual variability of the surface thermal condition in the winter. The heat budget anomaly in the summer is small due to the shallow mixed layer. The lateral heat fluxes in and out of the mixed layer caused by the change of the mixed layer depth can contribute to the heat budget of the central North Pacific. Effect of the interannual change of the velocity field occurred by the Ekman drift is smaller than that due to the change of the surface heat flux.

Interannual variability of surface currents in the tropical Pacific

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Keywords: El Nino, circulation

Drifter and current meter observations of near surface currents are used to investigate the interannual variability of circulation within 20 degrees of the equator. The seasonal variations are removed from the data and the coherent interannual patterns are extracted by a variety of statistical methods. This investigation closely follows Fankignoul et al. (J. Geophys. Res., 101, 3629-3647, 1996) who analyzed the first 6 years of the 13 year record of circulation. The focus of this work is on the development of circulation and the movement of warm water in the 1997-98 El Nino and the growth the maintenance of the 1998-99 La Nina. This analysis points out that the ocean current anomalies lead the large-scale patterns of SST anomalies. Can ocean currents observations be used to enhance the predictability of the onset of ENSO in the tropical Pacific is a question pondered herein.

Long-term variability of Ekman pumping velocity fields in the North Pacific

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Keywords: wind stress, Ekman pumping velocity, regime shift

By using sea level pressure(SLP) fields, we have reconstructed sea surface wind(SSW) fields for the period from 1899 to 1998. Moreover, based on those SSW fields, we have evaluated wind stress fields for the same period. In this study, we describe long-term variability of Ekman pumping velocity fields.

For the first step, we have applied empirical orthogonal function (EOF) analysis to the Ekman pumping velocity fields. The first EOF is highly correlated with PNA pattern and the second EOF is correlated with WP pattern. Correlation coefficients are 0.73 and 0.70, respectively, and statistically significant at 99 percent confidence level. In the time coefficients of the first EOF, we can find two climatic regime shifts. One is in 1940's and the other is in 1970's. Between these two regime shifts, the time coefficients have relatively higher value.

To describe the more detailed features of these regime shifts, we make three pictures of the standard deviations of Ekman pumping velocity for the period from 1920 to 1939, 1950 to 1969 and 1979 to 1998. The picture for the period from 1950 to 1969 is unique. The areal with large standard deviation is widely spread zonally and meridionally at the center of the North Pacific, while, in the other two pictures, large standard deviations are found on the edge of Aleutian low.

We also calculate the areal (177.5°W to 157.5°W, 37.5°N to 42.5°N) averages of 9-year moving standard deviations of wind direction. In this time series, we can find two regime shifts at 1940's and 1970's. In the period bounced by these regime shifts, the values of standard deviation are extremely high. In the same areal averages of 9-year running mean of wind speed, two regime shifts are found in 1940's and 1970's and wind speeds are slightly low in the period bounced by these regime shifts.

From the above results, we suggest that not only the intensity but also the shape and size of Aleutian low were vigorously changing in the period from 1940's regime shift to 1970's regime shift.

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Variations of the Kuroshio path between the continental slope and the Tokara Strait in the East China Sea

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Keywords: short-term variability, Kuroshio path, East China Sea, observations

The Kuroshio path between the continental slope and the Tokara Strait disperses with the largest displacement in the East China Sea. At the Tokara Strait its dispersion is observed as the north-southward shift of the Kuroshio axis with the periods around several ten days. In this study, typical spatial patterns of the Kuroshio path in this region are identified, composing data of WOCE surface drifter buoys during 1989 and 1996. Furthermore, the process generating the transition between the spatial patterns of the Kuroshio path is examined, using data of moored current meters deployed in the deep layers at three sites along the continental slope, and time series of the position of the Kuroshio axis at the Tokara Strait which is calculated from sea-level differences between tide-gage stations during March and November 1998.

Occurrence frequency of positions where 34 surface drifter buoys with the larger speed than 50 cm/s pass the Tokara Strait, is high at two locations, i.e., the northern and southern sides of the sea mount (called Yakushin-zone in Japanese). Trajectories of 9 drifters passing the northern and southern sides with the larger speed than 90 cm/s clearly show the different types of paths, the northern and southern paths respectively, between the continental slope and the Tokara Strait.

The variations of the deep current along the continental slope have the dominant periods about 20- and 50-days. These variations are characterized by the fact that the northward (southward) deep current along the slope is accompanied by high (low) temperature. This fact indicates that the northward (southward) deep current are generated by the horizontal shift of the Kuroshio axis toward the shallow (deep) side, which is probably associated with the passage of the Kuroshio meander with anticyclonic (cyclonic) circulation along the continental slope. The 50-days variation of the deep current near the location where the Kuroshio leaves the continental slope is strongly related to the north-southward shift of the Kuroshio axis in the Tokara Strait; the northward (southward) deep current, i.e., passage of the meander with anticyclonic (cyclonic) circulation, generates the southward (northward) shift of the Kuroshio axis at the Tokara Strait with the time-lag about 10 days.

These evidences suggest a process generating the transition between the northern and southern paths as follows; the Kuroshio meander with anticyclonic (cyclonic) circulation propagating downstream along the continental slope directs the Kuroshio to the east (north) near the location where it leaves the continental slope, and results in the southern (northern) shift of the Kuroshio path in the downstream side. This process is supported by a case study based on successive NOAA IR images.

Meridional flux variability in the south Indian Ocean

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Keywords: mass transport, watermasses, variability, circulation, Indian Ocean

Meridional exchanges between the Indian and Antarctic oceans are important to understand the variability of thermohaline circulation of the Indian Ocean. In the present study, an attempt has been made to estimate the variability in meridional transport at 32°S between Africa and Australia for three different sections. The oceanographic data collected onboard the Research Vessels Discovery during April-May 1936, Atlantis during June-July 1965 and Charles Darwin in November-December 1987 has been used.

The meridional flux is estimated by Montgomery and Stroup (1962) method with reference to the deepest common depth available between stations. The flux is represented with respect to longitude and also displayed in the Temperature-Salinity diagram. Thus, enables to quantify the contribution of different watermasses entering and leaving the Indian Ocean. The net transport is towards south in all the periods but shows long term variations. The variability of mass flux and the associated heat flux are determined. The spreading pattern of the Antarctic Watermasses are studied by carrying out T-S analysis for the South Indian Ocean(20°S-40°S).

Interannual variability in Pacific Ocean basin-scale circulation and transport during the 1990s

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Keywords: ocean circulation, heat transport, interannual variability

Interannual variability in the circulation of the Pacific Ocean has been observed throughout the 1990s using a combination of High Resolution XBT/XCTD (HRX) transects together with TOPEX/Poseidon altimetric data. The HRX network was created as part of WOCE, to observe variability of the upper ocean. It includes basin-spanning zonal and meridional transects, measuring boundary current and interior circulation, as well as choke point sections in the Southern Ocean and the Indonesian Throughflow.

Results indicate that basin-wide meridional geostrophic transport adjusts relatively quickly to changing wind stress, with net geostrophic transport tending to balance Ekman transport on periods longer than a year. Hence, ocean circulation and ocean heat transport reflect the dominant patterns of interannual atmospheric variability. Near the tropical/subtropical boundary of the North Pacific (22°N), poleward Ekman transport and equatorward geostrophic transport peaked in early 1994 and early 1997. This resulted in maxima in the shallow overturning circulation, with corresponding maxima in northward heat transport of about 1 pW, compared to a mean of 0.8 pW. In the subtropical South Pacific (31°S), the total mean meridional transport (13.0 Sv northward) nearly balances the Indonesian Throughflow (11.9 Sv westward). In this combination of South Pacific and Throughflow transects there are again maxima in the shallow overturning cell in 1994 and 1997 (i.e. export of the warmest layers from the tropical Pacific/ import of cooler waters), with corresponding heat export of about 0.6 pW compared to a mean of 0.4 pW. The large exports of heat from the tropical Pacific, about 1.6 pW in early 1994 and 1997 resulting from in-phase variability in both hemispheres, occurred about 6 months prior to development of mature El Nino conditions. The minimum heat export, about 0.8 pW, occurred in early 1998 during the developing La Nina.

Geostrophic transports from the HRX network are compared with TOPEX/ Poseidon altimetric data, with data-assimilating ocean models and with atmospheric analyses of air-sea heat exchange in order to test the consistency of the models and to make a preliminary examination of the total heat balance of the Pacific Ocean.

Distribution and circulation of the coastal Oyashio intrusion

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Keywords: Oyashio intrusion, Oyashio eddies, intermediate water, Oyashio-Kuroshio interfrontal zone

The distribution and circulation of the coastal Oyashio intrusion were examined with a CTD and shipboard ADCP survey conducted in the vicinity of the east coast of Japan in May 1994. The estimate of mixing ratios in the density

range of 26.4-27.2s_q, assuming isopycnal mixing between the pure Oyashio and Kuroshio waters, and the ADCP velocity data showed the following new results. (1) The distribution of the Oyashio water is horizontally and vertically patchy, and some of the Oyashio water patches formed mesoscale eddies with both cyclonic and anticyclonic circulations. (2) The anticyclonic Oyashio eddy had cold and low-salinity cores with low-potential vorticity (PV) suggesting that the origin was the Okhotsk Sea. The cyclonic Oyashio eddy with high-PV was considered to originate from the Western Subarctic Gyre (WSAG) in the north Pacific. We propose a new image of the intermediate Oyashio water circulation near the Oyashio-Kuroshio confluence, in which the eddies from the Okhotsk Sea and the WSAG play the significant roles.

Decadal variability of the Kuroshio transport derived from hydrographic data and coastal tide gauge data

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Keywords: Kuroshio transport, decadal variability, Sverdrup transport, sea-level

The Kuroshio is the western boundary current of the North Pacific subtropical gyre. Decadal variations of the Kuroshio transport are examined on the basis of 40 year long (from late 1950’s to present) hydrographic section data south of Japan and in the East Chine Sea. The decadal signals of the Kuroshio transport estimated from those data assuming the level of no motion at 1000 or 700 dbar are compared with those of the transport of western boundary current expected from the interior Sverdrup transport at mid-latitudes of the North Pacific calculated from the NCEP/NCAR reanalysis and COADS wind stress fields. The estimated Kuroshio transport south of Japan shows about 20-year period oscillation (peak-to-peak amplitude of ~ 15 Sv), which is in good agreement with the calculated transport of western boundary current with a lag of approximately 4 years and a bias of -4 Sv. On the other hand, the decadal signal of the Kuroshio transport in the East China Sea is quite weak compared with the Kuroshio transport south of Japan. These results suggest that (1) the Kuroshio transport south of Japan is probably adjusted to the decadal change in the basin-wide wind stress field, (2) the assumption of level of no motion holds approximately for the decadal time-scale, because isostasy is achieved for this time-scale, and (3) the basin-wide decadal signal can be propagated into the Philippine Basin over the Izu-Ogasawara Ridge but can hardly be propagated into the East Chine Sea over the Ryukyu Ridge.

Since the Kuroshio transport is known to be proportional to the sea-level difference across the Kuroshio, decadal variations of sea-level on both sides of the Kuroshio are examined in order to extend a time series of the Kuroshio transport south of Japan. The decadal signal of coastal sea-level observed by a tide gauge is compared with dynamic height at 200 dbar relative to 1000 dbar derived from hydrographic data on the offshore side of the Kuroshio. The variations of these two signals correlate well with each other, having almost the same amplitude (peak-to-peak amplitude of ~ 15 cm) and opposite phase. This result suggests that the decadal variability of the Kuroshio transport could be estimated from coastal tide gauge data alone, using a relationship between the Kuroshio transport and sea-level difference across the Kuroshio. The method is applied to a long-term (from late 1890’s to present) record of coastal sea-level south of Japan. The estimated transport is in good agreement with the observed transport of the Kuroshio south of Japan, mentioned above.

Comparison of the measured flows by the mooring system with the calculated flows by TOPEX/POSEIDON sea-surface height anomaly and the CTD observations on the OICE

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Keywords: Oyashio, direct current measurement, TOPEX/POSEIDON, geostrophic flow

About 17-month current records were recently obtained from a single mooring system with an Acoustic Doppler Current Profiler (ADCP) on the Oyashio Intensive observation line off Cape Erimo (OICE) which extends southeastward from Cape Erimo and agrees with the TOPEX/POSEIDON (T/P) grand track 060. During the current measurements the mooring system had been located at the area of influence of warm-core rings originated from Kuroshio-Extension. The flows therefore were considerably influenced by the warm-core rings. That is, the flows were baroclinic and their vertical velocity profiles were in good agreement with the geostrophic ones calculated from CTD observations. In addition, the measured fluctuating velocity components were relatively in good agreement with sea-surface velocities calculated from T/P sea-surface height anomaly (SSHA). From these results, we consider that the flow variabilities at this mooring station in the Oyashio area can be monitored by T/P SSHA. However, this mooring station was not located at the main part of the Oyashio jet. Geostrophic volume transports referred at 1000dbar on the OICE, which were obtained from 1992 to 1999, revealed that the main part of the Oyashio was located from 41.5°N to 42°N along the OICE. Now, we set additional mooring systems along the OICE (total seven moorings) and are under measurement of the flow of the Oyashio and a deep western boundary current.

The water circulation of the South China Sea in the condition of reversing monsoon and its contribution on the Pacific-Indian oceans through-flow variation

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Keywords: South China Sea, monsoon water circulation, Pacific- Indian oceans through-flow

The Asian monsoon system is one of the most important circulation systems in the general circulation of the global atmosphere. The water circulation of the South China Sea (SCS), one of the largest sea in the region, is principally determined by reversing monsoon winds. The results of the three-dimensional thermohaline and circulation modeling of the SCS show the possibility to estimate the water fluxes exchanged between Pacific and Indian Oceans via Indonesian seas and the interaction between SCS and Kuroshio Current (KC) system. There are two principal branches of the circulation in the SCS: one is permanently passing by eastern part of the sea from Bashi strait to Sulu Sea and another passing western part of the sea in direction to Java Sea in winter and from Java Sea in summer. The simulated permanent loop current in the northeastern region of the SCS shows the high intensity of the interaction between SCS and KC system. The development and application of the 3D regional atmospheric and marine models give the possibility to qualitatively study the processes air - sea interaction in the South East Asian monsoon activity region and its influence on the regional and global climate variability.

Session 5

Southern Ocean and Arctic Variability

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Multi-decadal changes of water masses in the Indian and Southern Ocean

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Keywords: multi-decadal changes, JARE, neutral surfaces, AAIW, UCDW

The Southern Ocean has a key role on the near surface to deep circulation of the world oceans and its temporal variability. However, the number of deep oceanographic observations available to describe the temporal variations is limited. Therefore, repeated observations in this region are very valuable for determining temporal variability of deep-water masses. From mid-1960's, the Japanese Antarctic Research Expedition (JARE) has made continuous observations from Freemantle, Australia, to Syowa Station (40°E, 69°S), Antarctica. Observations were also conducted from Antarctica to Cape Town (in mid-1960's to mid-70's), Mauritius (in mid-70's to late-80's), and Sydney (in late-80's to present). Data were obtained at about 420 locations over this region, and each cast averages 21 water samples. Historical data from Gordon et al.(1982) were also used to increase temporal and spatial coverage; these data were mainly taken in 1960's.

Temporal changes in salinity, potential temperature and pressure were investigated on neutral surfaces (Jackett and McDougall, 1997). To eliminate the effects of spatial gradients due to the differences in sampling locations, the WHP-SAC climatological estimates on neutral surfaces were interpolated and subtracted from the original observations. For about 20 years from 1960's-70's to 80's-90's, significant freshening/cooling occurred on the surfaces 26.8-27.0 kgm^{-3} equatorward of SAF along the 110°E meridional section. This is consistent with cooling and freshening signal at 43S for this period (e.g., Bindoff and Church, 1992) and the warming of this water mass. Along the zonal section south of 60S, a warmer more saline signal was significant on the surfaces 27.8-27.9 kg m^{-3}, which corresponds to the layers just beneath the mixed-layer at those latitudes (i.e. Upper Circumpolar Deep Water). Warmer more saline anomalies in 27.8 kgm^{-3} were also detected to the poleward of PF on the 110°E line. This suggests a possibility of weakening of surface mixing with CDW water below.

Temporal variability of water-masses and currents in the Southern Ocean inferred from observations

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Keywords: water masses, Southern Ocean, climate change

WOCE was largely designed to capture the synoptic picture of the large-scale ocean circulation during the 1980's and 90's. However, some of the exciting results are coming from observed differences in the important global water masses, long term measurements of the transport of the Antarctic Circumpolar Current, and monitoring of the Antarctic Circumpolar Wave. Using much of the available historical data and the modern WOCE sections from the Atlantic, Indian and South Pacific Oceans have shown systematic changes in the Subantarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW), Circumpolar Deep Water (CDW), and Antarctic Bottom Waters (AABW). SAMW in both the South Pacific and Indian sectors of the Southern ocean have warmed (cooled and freshened on density surfaces), leading to an increase in sea-level since the 1960's. The pattern of warming is broadly consistent with the observed increasing trend of sea-surface temperatures in the source regions of this water. AAIW in both of these sectors has freshened (by 0.06 psu in the Indian Ocean) and cooled slightly, suggesting a freshening in the source region, possible cause by increase rainfall over the Southern Ocean. North of the Sub-Antarctic Front CDW has shown little change. However, between the Polar Front and Antarctic, CDW has warmed (and become saltier on density surfaces) and the volume of AABW appears to have decreased. These changes are broadly consistent with the pattern of thermohaline circulation. Water masses close to their source (SAMW, AAIW) have warmed and freshened respectively, while CDW is mostly unchanged except where it is about to outcrop in the Antarctic Divergence. Model results of climate change show similar patterns of change in the water masses.

Analysis of the high frequency changes in XBT lines south of Tasmania and the repeat section chokepoints show highly variable transports (30 Sv), particularly north of the SAF. The integrated transport south of the SAF is remarkably constant. These same XBT data show the presence of the Antarctic Circumpolar Wave, extending deep into SAMW, but is relatively shallow south of the SAF. Model results show a that the observed ACW (mode 2 pattern, 4 years period) is much simpler than the ACW diagnosed from model output (mode 2 or 3 patterns and highly non-stationary patterns on decadal time-scales).

The spatial and temporal patterns of the Antarctic Circumpolar Wave in a coupled ocean-atmosphere model

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Keywords: natural variability, Antarctic Circumpolar Wave

To investigate natural variability and the Antarctic Circumpolar Wave (ACW) in the southern ocean we use output from the CSIRO/Antarctic CRC coupled ocean-atmosphere model (C15). Sixty-four years of the control model run is reported here, after an initial spin up of 1000 years. Some modifications over the earlier versions of this model, including improved topography in waters south of Australia make this model more suitable for examining natural variability in the southern ocean. We use potential temperature, salinity and velocity (21 depths, 66 longitudes and 29 latitudes in the Southern Hemisphere Ocean) and surface heat flux (66 longitudes and 29 latitudes in the Southern Hemisphere).

Hovmoeller diagrams of potential temperature anomalies along a streamline in the Southern Ocean are used to identify the ACW. Circumnavigating temperature anomalies clearly occur in the modelled southern ocean in shallow to intermediate depths (<1000 m). At 410 m, along a streamline where the speed of the Antarctic Circumpolar Current is a maximum, the speed of the strongest anomalies is approximately 4 cm/s. The strongest anomaly time-scales are 4-5 years (consistent with definition of ACW) and take approximately 20 years to travel around the globe. The anomaly strength is not uniform along this streamline. The strongest anomalies occur in the longitude band 100 to 200°E. Here the streamline moves relatively far south towards Antarctica. Although ACW variability with time-scales 4-5 years is the dominant signal, decadal variation with time-scales of approximately 40 years also occur. Below 1000 m the ACW shows a minor presence and the decadal variability is the dominant signal and persists to at least 2000 m.

The phase speed of these propagating signals decreases with depth. Scatter plots show a clear relationship between ACC current speed and phase speed throughout the water column. For each depth, the wave speed is calculated directly from the Hovmoeller plots for the more dominant propagating anomalies (ACW or decadal variability). This relationship is strongest at intermediate depths (500 to 1500 m.) where anomalies are most strongly advected and least subject to other influences such as convection, mixing and mid-ocean ridges. The principle spatial patterns of the anomalies are shown in an extended EOF analysis of the output from this model.

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A 25 year time series of the baroclinic transport of the Antarctic Circumpolar Current through Drake Passage

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Keywords: baroclinic transport, time series, Antarctic Circumpolar Current, Drake Passage, WOCE, lowered acoustic Doppler current profiler

Between November 1993 and January 2000 the Southampton Oceanography Centre and British Antarctic Survey have occupied the WOCE section SR1 across the Drake Passage five times.

The SR1 section runs from Burdwood Bank south of the Falklands to Elephant Island near the tip of the Antarctic Peninsula. The section consists of at least 29 full depth CTD stations that were supplemented in 1996 and 1997 with full depth lowered ADCP observations. All sections have all been made from the RRS James Clark Ross adding scientific value to her logistic runs to the British Antarctic bases on the Peninsula.

Including data gathered from the mid-70's the mean baroclinic transport above and relative to 0 cm/s at 3000 dbar is 110 Sv, (standard deviation (sd) = 5 Sv). Over this 25 year dataset no long term trend is evident but there are interannual signals with years of high transport around 115 Sv and years of low transport around 105 Sv. During the high transport years the Polar Front is found at a more northerly position than in low transport years. The more northerly position of these fronts corresponds to an influx of cold (—0.25°C) Antarctic Bottom Water southwards of the Polar Front.

For the WOCE years annual changes of the flux within layers defined by referenced potential density are examined. Within all layers the transport has weak variability. For example, the transport of intermediate water is 87 Sv (sd = 3.7 Sv).

A lowered ADCP gave estimates of the absolute velocity near bottom. North of the Polar front the bottom velocities are small around 2 to 5 cm/s. In contrast south of the Antarctic Circumpolar Current, the velocities are much larger, often around 15 cm/s. These correspond to eddies that are evident in the density field but with a strong barotropic signature. The section integrated transport (using mean station pair bottom track velocities as a geostrophic reference) give transports of 95 Sv and 152 Sv in 1996 and 1997 respectively. The bottom track velocities have a small random error and so the section integrated flux error is also small, between 3.5 and 4.5 Sv for bottom track velocity errors about 1 cm/s. For these two years the baroclinic transport relative to the bottom is 123 Sv and 144 Sv so that the LADCP bottom velocities imply 28 Sv of westward transport in 1996 and 8 Sv eastward transport in 1997.

In this poster we will extend the comparison of our flux estimates in Drake Passage with those from the ISOS mooring array and with transport estimates of the ACC at other locations.

Variability in the properties and circulation of water masses in Drake Passage and the Scotia Sea

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Keywords: Southern Ocean, deep water, water masses, Weddell Sea, Drake Passage

In 1999 we repeated two WOCE sections during the ALBATROSS cruise (Antarctic Large-scale Box Analysis and The Role Of the Scotia Sea). We present changes in water mass properties and deduce changes in circulation.

A21 was occupied by German WOCE in 1990, across Drake Passage. Relative to reference levels at 3000 m and the sea bed, we obtained the same values for the transport of the Antarctic Circumpolar Current (ACC) through Drake Passage (115 Sv and 160 Sv respectively). In 1999, Weddell Sea Deep Water (WSDW)was 0.015°C warmer and Upper Circumpolar Deep Water was 0.03°C warmer. Such changes should be considered in the light of the changes seen in bottom temperature at a bottom pressure recorder in southern Drake Passage. Four years of continuous bottom temperature revealed a cool anomaly between June 1994 and May 1995 of about 0.1°C, an order of magnitude larger than the changes seen between the two repeat sections. We discuss the origins of the cool anomaly, and the relative roles of variability in water mass formation, overflow at the South Scotia Ridge and movements of the ACC fronts.

A23 was occupied by UK WOCE in 1995, nominally along 35°W across the Weddell Sea, eastern Scotia Sea, and Argentine Basin. During ALBATROSS we repeated the eastern Scotia Sea portion of A23. In 1999, Warm Deep Water (WDW) south of the Southern Boundary of the ACC(the Scotia Front) is approximately 0.1-0.2°C warmer due mainly to raised WDW temperatures in the Weddell Sea being fed through to the Scotia Sea as the WDW flows northwestward in the Weddell Gyre. There is a warming of the WSDW of approximately 0.05°C, and an accompanying change in salinity to maintain the potential temperature-salinity relationship. This is caused by variability in the properties of the water overflowing the South Scotia Ridge, rather than enhanced outflow of the bottom layer of the Scotia Sea or movements of the ACC fronts, and may be related to changes in the intensity of the Weddell Gyre circulation. Comparison with the Drake Passage bottom temperature records suggests that the colder WSDW of 1995 is likely to be the anomalous case, rather than the warmer WSDW of 1999. In addition, the deepest layer of WSDW south of the Southern Boundary is more saline in 1999 than 1995, with no corresponding change in potential temperature. This is due to an intrusion of dense WSDW from around the South Sandwich Arc and southward through Georgia Passage. Variability in the direction of the abyssal flow through Georgia Passage may be due to meanders of the Southern Boundary, or changes in the density of the overflow at the South Scotia Ridge

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What causes the decaying trend in the Arctic ice cover; polar vortex, clouds or ice-albedo feedback?

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Keywords: Arctic, global warming, sea ice, radiation

The ice cover in the Arctic Ocean is reducing along with decadal variability in the last 40 years. The trend is attributable to atmospheric conditions, among which the summer cloud reduction is the most critical. This cloud trend permits more solar heating and consequent ice reduction, and is possibly caused by a weakening in transport of the humid air mass from the East Asia-Pacific region. An additional contribution is made by increasing winter cloudiness, which reduces outgoing longwave radiation. The increased winter clouds can be the result of a regional phenomenon of moisture associated with synoptic cyclones. The positive ice-albedo feedback associated with more open water, which absorbs more solar radiation, also contributes to further ice reduction. A minor contributor is atmospheric circulation associated with the intensifying polar vortex, which can dynamically and thermodynamically reduce the ice cover. These characters should be compared with model simulations of global warming, and will give a hint to whether the ice reduction is related to anthropogenic change or natural climate variability.

Appendix 2.S5

Interannual variability of Arctic Ocean temperaure and salinity fields fifties-eighties by spectral analysis

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Keywords: Arctic Ocean, annual temperature and salinity fields, temporal and spatial variability, Atlantic inflow linkages

Lack and unevenly location of oceanographical observing sites for Arctic Ocean was a principal cause of absence of related variability studies. Spectral analysis was developed to overcome these problems. The basic idea of spectral analysis is to represent all available observational information in compressed form to minimize losses in accuracy. A well known spectral method is principal component analysis (PCA)[Hotteling method] expressed in terms of two -dimensional empirical orthogonal functions (EOF's). The combined spatial and temporal interrelationship of observational data can be expressed as a biorthogonal expansion closely related to known SVD (singular value decomposition) of observational matrix. The EOF's and the corresponding expansion coefficients are usually referred to as the principal components (PC) and describe the temporal modes. For each temporal mode a separate set of EOF's are calculated. Its values in missed grid points had been interpolated by kriging technique. Spectral method assumes a priori covariances of expansion coefficients to be known. The estimated a posteriori error covariances of expansion coefficients and the estimated a posteriori error covariances at the grid points are determined by some nonlinear relationships contained observation error covariances and a priori covariances of expansion coefficients as well as EOF's values at observational sites and grid points. Oceanological applications of this method are considered. Reconstructed and error fields of water temperature and salinity for 20 depth levels in Arctic Ocean for 40 year data set are discussed. In the present application, intensive statistics were derived for the 70's decade which provided good temporal and spatial sampling. Statistics obtained from the spectral analysis procedure were then applied to the other three decades (50's, 60's, and 80's) which all contain areas under-sampled during all years of the decade. Relationships between Atlantic inflow anomalies and related peculiarities of Arctic circumpolar patterns are analysed. Annual patterns of NAO index as well as Arctic circulation pattern were classified by fuzzy logic approach. It was appeared that there are some relationships between annual NAO index anomalies and temperature of ascending Atlantic water branch from Nordic seas to Arctic basin. Some linkages between NAO index anomalies and Arctic circulation patterns had been revealed. EOF's temperature and salinity field analysis had been performed for variability study. First EOF explains 17-19% of STD (standard deviation) for salinity fields at 0 - 300 meter depth band and 11-13% of STD for temperature fields at the same depths. Temporal dependencies of EOF's expansion coefficients had been calculated. First EOF coefficient time series reveals fast 2-3 yearly oscillations at the beginning of 50's and at the end of 60's for the surface level. Therefore, 50's and 60's temperature variability exceeded the same values for other decades. In contrary, at 100-300 meter levels dominate the oscillation of 3-5 year scale for 50's and 60's. Early products from spectral objective analysis have been included in the Arctic climatic digital atlases.

Arctic climate variability during 20th century from observations and model results

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Keywords: Arctic, ocean, ice, and atmosphere variability

Arctic atmosphere oscillation (AAO) and Arctic Ocean Oscillation (AOO) are discussed using EOF and correlation analyses of the observed and simulated sea level pressure, surface air temperature, ice conditions, sea level heights, precipitation, river run-off and permafrost data. Observed data are from different sources and are partially reconstructed to cover period 1899-1999. The simulated results are from the 300-year run of the National Center for Atmospheric Research (NCAR) Climate System Model (CSM), and from a two-dimensional barotropic coupled ice-ocean model forced by winds calculated from the observed and simulated SLPs. Analysis of the North Pole SLP (1899-1999) shows that atmospheric pressure has been decreasing during the 20th century with a trend of about 1 hPa per decade. This trend is in agreement with

increase of the surface air temperature. Arctic warming during 1920s and 1930s and after 1989 are well pronounced in the atmospheric pressure fields and air temperature records. Before 1946, the simulated wind-driven ice and ocean circulation in the arctic is one-directional (anticyclonic), and decadal variability is manifested only in the intensity of this circulation. After 1946, two circulation regimes of the wind-driven circulation dominate. Ice and water motion alternates between anti-cyclonic and cyclonic, with each regime persisting for 5-7 years (period is 10-15 years). NCAR CSM results reveal the AAO which first mode pattern is similar to the observed pattern of the AAO but simulated gradients of the SLP are smaller than in observations. The NCAR CSM wind-driven ice and water circulation is very stable and is always anticyclonic.

Arctic Ocean Model Intercomparison Project

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Keywords: Arctic Ocean, modeling, ice and water circulation, climate variability

The Arctic Ocean Model Intercomparison Project (AOMIP) is an international effort to identify systematic errors in Arctic Ocean models under realistic forcing. The main goals of the project are to examine the ability of Arctic Ocean models to simulate variability on seasonal to interannual scales, and to qualitatively and quantitatively understand the behavior of different Arctic Ocean models. AOMIP's major objective is to use a suite of sophisticated models to simulate the Arctic Ocean circulation for the periods 1946-1998 and 1899-1998. Forcing will use the observed climatology and the daily atmospheric pressure and air temperature fields. Model results will be contrasted and compared to understand model strengths and weaknesses. AOMIP brings together the international modeling community for a comprehensive evaluation and validation of current Arctic Ocean models. AOMIP will provide valuable information on improving Arctic Ocean models and result in a better understanding of the processes that maintain the Arctic's observed variability.

Baroclinic transport variability of the Antarctic Circumpolar Current south of Australia (WOCE repeat section SR3)

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Coauthors: Serguei Sokolov

Keywords: Southern Ocean, baroclinic transport variability

Baroclinic transport variability of the Antarctic Circumpolar Current (ACC) near 140°E is estimated from six occupations of a repeat section occupied as part of the World Ocean Circulation Experiment (WOCE section SR3). The mean top-to-bottom volume transport is 147±10 Sv (mean ± 1 standard deviation), relative to a deep reference level consistent with water mass properties and float trajectories. The location and transport of the main fronts of the ACC are relatively steady: the Subantarctic Front carries 105±7 Sv at a mean latitude between 51°S and 52°S; the northern branch of the Polar Front carries 5±5 Sv to the east between 53°S and 54°S; the southern Polar Front carries 24±3 Sv eastward at 59°S; and two cores of the southern ACC front at 62°S and 64°S carry 18±3 and 11±3 Sv, respectively. The variability in net property transports is largely due to variability of currents north of the ACC, in particular an outflow of 8±13 Sv of water from the Tasman Sea and a deep anticyclonic recirculation carrying 22±8 Sv in the Subantarctic Zone. Variability of net baroclinic volume transport is similar in magnitude to that measured at Drake Passage. In density layers, transport variability is small in deep layers, but significant (range of 4 to 16 Sv) in the Subantarctic Mode Water. Variability of eastward heat transport across SR3 is significant (range of 139°C Sv, or 0.57 x 10^{15} W, relative to 0°C), and large relative to meridional heat flux in the southern hemisphere subtropical gyres. Heat transport changes are primarily due to variations in the westward flow of relatively warm water across the northern end of the section. Weak (strong) westward flow and large (small) eastward heat flux coincides with equatorward (poleward) displacements of the latitude of zero wind stress curl.

A six year record of baroclinic transport variability of the Antarctic Circumpolar Current at 140∞E, derived from XBT and altimeter measurements

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Keywords: Southern Ocean, baroclinic transport variability, altimeter measurements

Repeat hydrographic sections across the Antarctic Circumpolar Current are used to derive an empirical relationship between upper ocean temperature and the baroclinic transport streamfunction. Cross-validation shows this relationship can be used to infer baroclinic transport (above and relative to 2500 m) from XBT temperature measurements with an error of a few per cent. The mean transport distribution derived from 31 austral summer XBT sections over a six year period consists of westward flow immediately south of Tasmania, a broad band of strong eastward flow between 50°S and 55°S, and three cores of eastward flow south of 55°S. The mean net transport in each austral summer shows a smooth variation, with a minimum in 1993-1994 and 1994-1995 and a maximum in 1996-97. By defining a second empirical relationship between surface dynamic height and baroclinic streamfunction, a baroclinic transport time series is derived from altimeter measurements of sea surface height. While errors are larger than for the XBT estimates, transports derived from altimetry agree well with in situ estimates, suggesting baroclinic changes make the dominant contribution to sea level anomalies. The continuous transport time series from altimetry suggests the irregular XBT sampling aliases variability at unresolved time-scales, and the smoothly-varying interannual signal apparent in the XBT transports is spurious. Sea level variations in the mesoscale (3-4 weeks), quasi-annual, and interannual bands make roughly equal contributions to the total variance. The transport variations are correlated with local changes in both wind stress and wind curl, but the transport time series is too short to draw statistically significant conclusions.

The subsurface structure of interannual SST anomalies in the Southern Ocean

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Keywords: Southern Ocean, Antarctic Circumpolar Wave, repeat XBT sections

A 7 year time series of repeat XBT sections between Tasmania and Antarctica are used to describe the subsurface structure of temperature anomalies across the Southern Ocean. In general, the interannual temperature variations in the upper 700 m result from the meridional shifts in the position of the main fronts rather than from downward propagation of temperature anomalies generated at the sea surface. The latter is predominant in the region of Subantarctic Mode Water formation and possibly near Antarctic continental margin. The subsurface temperature changes include variations in the Antarctic Circumpolar Wave (ACW) frequency band (with periods of 2—7 years) and longer period signals (‘quasi decadal variability’). Sea surface temperature data show the variability is of comparable magnitude in these two frequency bands (meridional mean standard deviation of 0.25°C and 0.19°C respectively). The low frequency variability strongly modulates the ACW signal, suggesting similar low frequency modulation of the impact of ACW anomalies on rainfall in Australia.

Upper ocean variability in Drake Passage from XBT and satellite measurements

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Keywords: thermal variability, Drake Passage, cold-core eddies

A combination of both long-term hydrographic and altimeter measurements are used to describe the time-varying circulation of the upper ocean in Drake Passage. Year-round monitoring of the upper-ocean temperature variability in Drake Passage has been undertaken approximately bimonthly since September 1996 via a high-resolution XBT sampling program. Few observational data are available for Drake Passage during the harsh winter months, and thus the XBT program and the altimetric data provide a fascinating insight into the evolution of the surface and subsurface thermal variability over the four-year period. During the September survey of each year of the XBT program, a cold-core feature is found within the Antarctic Polar Frontal Zone. The complementary data sets are used to examine the evolution of the cold-core rings, and the subsequent effect on the heat content and geostrophic mass transport within Drake Passage. The cold-core eddies are found to be a very efficient mechanism for water mass exchange between the subantarctic surface water masses to the north, and the Antarctic water masses to the south.

The development of the 1997 warming and freshening event in the Beaufort Sea

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Keywords: sea ice, warming, frehening, mixing

The climatic state in the Beaufort Sea in 1997 was characterized by warmer atmosphere, smaller areal coverage of sea ice in summer than average, and an oceanic mixed layer with a relatively low salinity that persisted into fall and early winter. The most remarkable change occurred near the end of 1997 when both the salinity and temperature in the upper layer varied significantly in a short-time period. The evolution of the air-sea-ice condition was observed by an autonomous buoy. In this study, we used these buoy data together with satellite-observed sea-ice concentration to study physical mechanisms for changes in the coupled ocean-ice system. Our study indicates deep vertical mixing driven by an intense storm was likely to be responsible for a profound change in the mixed layer near the end of 1997. The changes in air temperature, solar radiation and melting/freezing of sea ice were important for the more gradual change in the Beaufort Sea in 1997. Similar events were inferred from storms in the Eurasian basin in 1994. We postulate that synoptic storms plays a very important role in the variations of the heat and salt budgets in the upper Arctic Ocean.

Session 6

Atlantic Variability

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Friedrich Schott

Interannual variability of natural and anthropogenic carbon and transient tracers in the Labrador Sea

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Keywords: Labrador Sea, carbon, transient tracers, anthropogenic CO_2, interannual variation

Inorganic carbon and transient tracers (CFC-11, CFC-12, CFC-113 and CCl4) have been measured annually since 1993 along the WOCE AR7W section in the Labrador Sea. Deep convection in the Labrador Sea in late winter produces a well-ventilated water mass, the Labrador Sea Water (LSW), which is an important vehicle for the transport of atmospheric gases, including carbon dioxide and transient tracers, to intermediate depths of the North Atlantic Ocean. The AR7W section also includes the North East Atlantic Deep Water (NEADW) and the Denmark Strait Overflow Water (DSOW) at depth, which are ventilated in the Nordic Seas. Salinity and temperature characteristics as well as the volume of these three water masses in the Labrador Sea are highly variable and not coherent. Interannual variation of total inorganic carbon, anthropogenic carbon dioxide, contribution of total carbonate due to biological processes, and transient tracers are investigated together with the salinity and temperature characteristics of each water mass.

Vertical distributions of anthropogenic CO_2 compare favorably with those of the conservative tracers, especially CFC-12. The three principal water masses in the Central Labrador Sea are clearly defined by profiles of both anthropogenic CO_2 and tracers. The concentrations of these tracers decrease in correspondence with the ages of water masses of 0-2 years, 6-9 years and 10-15 years for LSW, DSOW and NEADW respectively. Concentrations of tracers have increased since 1993. Due to the uncertainties and assumptions used in the calculation of anthropogenic CO_2, the method is not robust enough to resolve the interannual variation that is evident in the CFC-12 measurements. The inventory of CFC-12 in the Central Labrador Sea has increased in recent years, while the inventory of anthropogenic CO_2 does not show any trend. Each component of the anthropogenic CO_2 calculation, including biological processes and disequilibrium at the surface, will be assessed to determine the source of the discrepancy between anthropogenic CO_2 and tracers.

Exchange processes over the Greenland Scotland Ridge

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Keywords: subpolar North Atlantic, overflow, passages, exchange processes

A regional model of the North Atlantic (50°N-75°N) is used to study the processes that control the exchange of water mass and heat between the Greenland Sea and the subpolar North Atlantic across the sills of the Greenland Scotland ridges. The pathways of the cold overflow waters that feed the NADW are described. The strength of the net heat exchange between the polar and subpolar basins is shown to be insensitive to mixing process in the overflow plume but depends on the large-scale wind forcing pattern. Influences of heat flux variations over the Greenland Sea on the net heat exchange will be discussed and transport patterns are compared to recent observations in and over the Denmark Strait.

On ocean dynamics in mid-latitude climate

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Keywords: NAO, coupled models, process study

Several recent models of mid-latitude climate have speculated on the role of the North Atlantic ocean in modulating the North Atlantic Oscillation (NAO). Here this role is examined by means of numerical experimentation with a quasi-geostrophic ocean model underneath a highly idealized atmosphere. It is argued that the dominant mid-latitude oceanic influence is due to the so-called inertial recirculations, rather than linear baroclinic waves as have previously been studied. In these experiments, the forced response of the inertial recirculations dominates the leading order ocean mode of variability, but that mode is energized by oceanic intrinsic variability. The oceanic effect is amplified relative to that produced by waves, although the end state role of the ocean is to damp NAO at longer time scales. The damping reflects competition between intrinsically driven intergyre heat flux and an opposing feedback driven advective heat flux. Spectral extrema can result at the transition point where the feedback heat flux takes control, although the peaks are secondary phenomena. The primary coupling effect is the suppression of variability in the interdecadal band. The timescales associated with the suppression are associated with the adjustment process of the inertial recirculation. The picture of mid-latitude climate variability painted here has qualitative similarities to that obtained from the linear waves models, but differs fundamentally from them both dynamically and philosophically. Most importantly, ocean variability is a dominant, rather than semi-passive, partner in all aspects of the coupled system.

Atlantic Ocean variability: Messages from the past and challenges for the future

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Keywords: Atlantic, decadal-change, CLIVAR, GOOS

The Atlantic Ocean is by almost any measure the best-observed of all the oceans. It has some of the oldest hydrography data sets of known quality and the North Atlantic, in particular, can provide data of the high spatial resolution.

Examination of these measurements in the light of observations made by WOCE has allowed us to construct a picture of decadal scale changes of temperature (and in some cases salinity) throughout the watercolumn and revealed significant subsurface change. The key role of the Atlantic in the global thermohaline circulation gives added importance to the documentation of these changes at high latitudes.

This review of Atlantic Ocean variability will present what we now know of (generally) decadal changes in the physical properties of the waters of the Atlantic and of their circulation. It will point to the significance of these changes both locally and in relation to the global ocean.

Based on this knowledge, a case will be made for further studies of Atlantic Ocean variability both in CLIVAR and as part of the developing Global Ocean Observing System (GOOS)

Appendix 2.S6

Large-scale long-term changes in the North Atlantic Ocean as inferred from the high-quality hydrographic dataset: The 1950s versus the 1990s.

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Keywords: WOCE, North Atlantic Ocean, decadal variability, hydrographic atlas, circulation

For the WOCE Hydrographic Atlas of the Atlantic Ocean we have compiled an extensive composite dataset that includes both historical and WOCE observations. All the data were statistically quality checked to eliminate random errors in the data, followed by a procedure to estimate and identify systematic errors in the data specific for each particular oceanographic cruise. The resulting refined dataset provides the basis for an optimal interpolation of oceanographic parameters on neutral surfaces for selected, i.e. decadal time periods. A comparison of calculated property fields focussed on areas with low estimation errors.

We also compare changes of the property fields with variability pattern revealed along repeat hydrographic lines such as WOCE A1 and A2 in the North Atlantic. We identify areas of distinct changes in hydrographic properties and large-scale pattern for the IGY years of the 1950s and the WOCE years covering the 1990s.

Interannual variability of the Labrador Sea circulation: A synthesis of TOPEX/Poseidon, WOCE, and NCEP/NCAR data

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Keywords: interannual variability, volume transport, sea level, North Atlantic Oscillation, WOCE hydrography, TOPEX/Poseidon altimetry

The interannual variations of the Labrador Sea circulation are studied based on seven years of TOPEX/ Poseidon altimetry, WOCE hydrographic observations and NCEP/NCAR reanalysis data. The TOPEX/ Poseidon sea level data and WOCE density data are combined to compute the volume transport in the Labrador Sea. The NCEP/NCAR wind and sea level pressure data are used to explore the relationship between the transport and sea level variability and the North Atlantic Oscillation (NAO). The implications of the interannual variability are discussed in relation to water mass formation, thermohaline circulation and climatic variability in the North Atlantic.

From 1993-1999, the sea level in the deep Labrador Sea has a range of about 0.1 m in winter, lowest in 1994 and increasing afterwards. The summer sea level change is much smaller, about 0.03 m. The winter change is correlated with the winter air temperature over the Labrador Sea, in response to intensification and relaxation of the convective overturning in the upper and mid water column. The summer variation is correlated with the summer air temperature as a result of thermohaline expansion/contraction of the seawater.

The volume transport of the Labrador Sea gyre is estimated from TOPEX/Poseidon and WOCE data using the linear momentum equation and the hydrostatic approximation in which the sea surface is the level of known motion. The interannual variation of the total transport in spring/summer has a range of 6 Sv, and is positively correlated with the fall/winter NAO index and wind patterns in the northwest North Atlantic. The total transport anomaly is decomposed into a barotropic and a baroclinic component. The interannual change of the barotropic transport is similar to that of the total transport, and is positively correlated with the fall/winter NAO index. The baroclinic transport anomaly, in comparison, has a smaller magnitude and the opposite sign. We conjecture the interannual variation of the total spring/summer transport is mainly attributed to the fluctuation of the past fall/winter wind stress curl associated with the Icelandic Low. The deepened Icelandic Low in high index years generates a strong cyclonic wind stress curl which in turn creates a strong divergence and a large upward sea surface slope toward the East Greenland coast, resulting in an intensified Labrador Sea circulation through large-scale advection.

Quasi-biennial motions in the depths of the Brazil Basin

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Keywords: quasi-biennial, DBE, rafos floats

Neutrally buoyant floats were tracked over a period exceeding 5 years near 2500 m and 4000 m depths within the Brazil Basin as part of the Deep Basin Experiment. Their purpose was to quantify the mean circulation over the measurement period within the North Atlantic Deep Water and Antarctic Bottom Water layers. Amongst other reasons, the Brazil Basin was chosen for this study because it contains a remarkably quiet mesoscale eddy field with values of the eddy kinetic energy of around $1 cm^2 sec^{-2}$ in the interior. However, the absence of energy at mesoscale periods brings into focus energy at longer periods and there do appear to be propagating baroclinic Rossby waves with periods of order 2-3 years. Evidence for this motion will be presented and speculations as to their cause given.

Interannual variability of regional subpolar mode waters of the northeast North Atlantic

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Keywords: Iceland Basin, Rockall Trough, subpolar mode water, air-sea interaction, advection

The classic view of subpolar mode water development is a slow steady path moving cyclonically around the subpolar gyre making a smooth progression from low density in the south and east, towards higher densities around the gyre (McCartney and Talley 1984). The SPMW is characterised by thick layers with low stratification generally thought to be formed in winter, with mixing to 400-600 m in many places and up to 1500 m in regions such as the Labrador Sea. A more recent view was put forward by Talley (1999, WOCE International Newsletter). By collating data from several WOCE hydrographic sections in 1997 the SPMW was mapped horizontally and the result rather different. A series of SPMW “types”, each identified by a PV minimum, but existing as discontinuous density classes, bounded by steeply sloping isopycnals and bands with no SPMW layers. The “blocks” of SPMW tend to be associated with the topography perhaps because they form in regions of sluggish throughflow, or increased mixing over topographic features.

In this poster we examine the nature of the interannual variability of a series of local mode waters observed in the northeast North Atlantic on an annually repeated hydrographic section between Scotland and Iceland during the 1990’s. The repeat section occupied by Southampton Oceanography Centre extends the Rockall Trough section begun in 1975. The low potential vorticity of the winter mixed layer is preserved below the seasonal pycnocline, and defines a body of water that represents conditions at the end of the previous winter. By examining properties of the low PV core of individual mode waters we distinguish changes across the sections caused by mesoscale features and frontal locations from those affecting the mode waters themselves. The mode waters of the Iceland Basin exhibit relatively high temperatures since 1995 compared to 1990, peaking in 1998. In the Rockall Trough the temperatures in early 2000 are the highest seen in the 25 year time series. Salinities in the Iceland Basin and Rockall Trough decreased after 1990, reached a low in 1996 (end of winter 1995) but rapidly increased since then and peaking in 1998. The relative effects of air-sea interaction and advection in modifying the mode water properties will be explored.

Appendix 2.S6

Transport variability across “48°N” in the North Atlantic: An oceanic index of climate variations in the North Atlantic?

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Keywords: WOCE, North Atlantic Ocean, meridional heat transports, decadal variability, North Atlantic Oscillation (NAO)

First analyses of the coherent hydrographic data set along the so-called “48°N”-section between the English Channel and the Grand Banks of Newfoundland show significant interannual changes in the climate relevant key parameters of the large-scale circulation in the North Atlantic such as heat and freshwater transports. The data consist of five available sets of the WOCE/A2-section during the Nineties for the years 1993, 1994, 1996, 1997, 1998 and of two previous transatlantic cruises in April of 1957 and 1982. The recent almost-annual data sets exhibit a short-term variability that appears to be a close reflection of the extreme interannual behaviour of the NAO-index since 1993. The meridional heat transport drops from 0.70 PW in 1996 to 0.30 PW just one year later, following the decline of the NAO-index between winter 1995 and 1996, and recovers equally rapidly to 0.60 PW in summer 1998 when the NAO-index returns to positive values. The two earlier estimates of the heat transport in 1957 and 1982 are not inconsistent with this behaviour of a fast oceanic response to atmospheric fluctuations. The observed temporal changes in the heat transport seem to reflect changes in the NAO-index with a time-lag of about one year. For this phase lag the changes in the NAO-index explain 70% of the changes in heat and 65% in freshwater transports as well as 60% in the meridional overturning rate — the transport of the upper layer of the Meridional Overturning Circulation (MOC). Though based on only few occupations, this dramatic behaviour may be a first indication that a short-term change in atmospheric forcing, however extreme, may be matched by an equally rapid response in the large-scale ocean circulation. The “dynamical response” across the “48°N”-section is most pronounced in the central Newfoundland Basin.

Decadal changes in the deep North Atlantic’s diapycnal mixing

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Keywords: diapycnal mixing, decadal variability

Diapycnal mixing is examined in inverse box models of the North Atlantic, bounded by hydrographic sections across 24.5°N and 48°N. The model solves for reference velocities and equivalent diapycnal velocities (a parameterization of diapycnal advection, diffusion and eddy transport) in neutral density layers, with air-sea forcing derived from the COADS monthly fields. Separate inversions are performed for 1957, the early 1980s, and the 1990s. It is shown that the diapycnal fluxes in the deep ocean layers are larger during the early 1980s, compared to the earlier and later periods. These changes may be related to the production rate of Denmark Straits Overflow Water and temporal changes in the structure of the North Atlantic Meridional Overturning Circulation.

Seasonal to interannual variability of boundary currents in the Labrador Sea: Observations and model results

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Keywords: Labrador Sea variability, western boundary currents transport

Intensive studies of convection activity, currents and boundary circulation have been carried out by the Kiel Sonderforschungsbereich (SFB) 460 in the Labrador Sea since 1996. During this time period, significant variability of deep convection was observed. The seasonal cycle and interannual variability of Labrador Sea mixed-layer depths, mesoscale eddy energy and western boundary currents are presented, based on the analysis of moored arrays, ship sections, drifters and altimetry.

The observed patterns of variability can also be identified in eddy-permitting and eddy-resolving numerical models. Process studies within the context of FLAME (Family of Linked Atlantic Models) allow the attribution of different modes of variability to specific generation mechanisms such as direct wind forcing and the influence of convective activity. While the mean annual cycle is close to that predicted by simple linear models in topographic Sverdrup balance, changes in phase and amplitude are introduced by convection. An increase in variability on synoptic time scales is clearly evident during phases of strong convection.

Participant List

Appendix 3

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Figure Caption

Participants in the photograph are (from left to right):
sixth (back) row: Sokov, Komori, Uchida, I. Kaneko, Miyamoto,Stammer, Park, Sprintall, Goda, Kashima;
fifth row: Yang, Toyoshima, S. Aoki, Nakamura, Dinh, Shimizu,Awaji, Zhu, Ishikawa, Gulev, Hurrell, Chapman, Umatani, Fukasawa;
fourth row: Hatayama, Kitamura, Suga, Peter, Aoyama, Josey, Ito,Uehara, Boening, Killworth, Dewar, D.-K. Lee, H.-J. Lie;
third row (right-hand-side two third): Naveira-Garabato, A. Kaneko,Proshutinsky, Alexiou, Wakata, Hishida, Sugimoto, Takeuchi;
second row: Ichikawa, Matsuo, Otoki, Gould, Holliday, Hanawa,Nagata, Swift, Azetsu-Scott, Banks, Lumpkin, Y. Aoki, Tokmakian, Boscolo, Cunningham; and
first (front) row: Haak, Cornuelle, Beal, Lotfi, Le Traon, Webb, Imawaki, Joyce, Roemmich, Koltermann, Large, Bindoff, Chelton, Kubota.

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